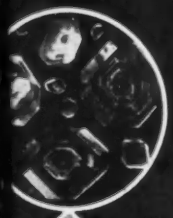
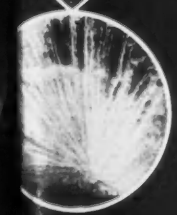
Atomic Facts Issue

CHEMISTRY





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Editorial:

Newer Atomic Knowledge
Inside Front Cover

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Newer Atomic Knowledge

➤ FIFTY YEARS *have seen the unfolding of nuclear science. As this century opened a few pioneers were beginning to realize that the newly discovered phenomena of radioactivity must originate inside the atom. Lying much deeper than the region of chemical change, the factors responsible for radioactivity kept constantly at work no matter what chemical transformations befell. The atom changed from a theoretical point to a world waiting for exploration.*

The nucleus of the atom has had its structure described much more recently. Developments of the decade since atomic fission was discovered have changed scientific thought more rapidly than any other ten-year period one can recall. Revelation, during the past five years, of information previously kept secret for military purposes, together with current reports of new developments, has resulted in an unprecedented flood of new material on the subject of atomic energy.

This collection of ATOMIC FACTS *brings together the newer knowledge on the subject, in an attempt to summarize it as of the present time.*

Authoritative articles explaining various phases of atomic science have appeared constantly in CHEMISTRY *during the past five years. The most timely and useful of them are here collected, together with additional material to complete an overall picture of nuclear science today. The significant steps in our understanding of the atom and its particles are gathered into this compilation for reference.*

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Our Atomic Future

by Watson Davis

➤ If A or H bombing ever comes to America, what can people do about it?

We can of course bury our heads in our great cities of brick and concrete and steel and do nothing about the danger — until and if it comes.

This may be the most realistic thing to do. It may be wise to take the "calculated risk," as the admirals and generals would put it, that strong arms and our tough attitude against the Soviets will prevent total war. Or we may have faith that there will come a change on the part of the Soviets that will restore the possibility of peace to the world.

To make our nation reasonably safe against the effects of atomic bombing might be more devastating than war itself. Our key industries would have to be put underground. Our giant cities would have to be abandoned. Millions of new homes would have to be fanned out in vacant, remote places. For a decade or more all of us would have to think day and night of preparing for the bombing to come. This would wreck all normal progress. Certainly controls far more rigid than any imposed before in America would be necessary. We would have to accept a dictatorship of our daily lives.

For those who expect to live above ground in areas that are likely targets, the possible methods of protection are meager but troublesome. There is no hope of helping those in the center zone of bomb damage. They will be killed outright or die shortly thereafter in most cases.

On the outskirts of the bomb burst, it may be helpful to wear a lead shield over your liver or to shoot yourself full of a protective hormone, before the bomb explodes.

The trouble with all this is that the suspense as to when a bomb is likely to be dropped may extend over years, during which precautionary measures will become just not worth the trouble.

Experts seriously argue these days that it will be unrealistic to attempt to defend the largest American cities from H-bomb attack in the sense of preparing them to resist such an explosion. New York, Chicago, Philadelphia and other cities of over a million or so are just too big and too concentrated in their populations to do anything that would be effective. The assumption is made that an enemy could get one H-bomb on a target even if our radar and countering planes and missiles were very effective and accounted for most of the bombs that were launched.

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With the development of long-range airplanes and gigantic guided rockets, distance and the oceans have lost their value as barriers against aggression. The rising tide of easy war puts into our hands the means of world suicide.

Our prime defenses, of necessity, must consist of appeal to the reason and emotions of mankind throughout the world. Nevertheless, we must store our plutonium and tritium as our forefathers kept their powder dry.

Radioactive Death Curtain

Radioactivity from superbombs could completely destroy life on a whole continental area. That is one of the threats of the hydrogen bomb to our civilization. The complete destruction of a large city by one H-bomb is appalling enough. But experts see even grimmer possibilities in the radioactivity that can be produced by the superbombs.

Radioactive materials in great amount could be flung into the atmosphere if the conditions of the explosion of the hydrogen bomb were carefully selected. Actually the effects of neutrons and hard gamma radiation (X-rays) from a hydrogen bomb would not extend much farther from the blast center than they would in the case of an atomic or fission bomb.

The debris of a hydrogen bomb would not be much more radioactive than remains of the uranium or plutonium bomb set off within it to trigger it. But a great blast of neutrons and other radiation would be produced, extremely intense within the explosion area. This radiation could be used to create radioactive poison contaminants of the atmosphere in large quantity. For many miles away from the blast and damage area fine particles of what amounts to "artificial radium" would fill the air and be transported on every wind, sickening man, beast and plants alike and wiping them out.

Explode a series of H-bombs in the Pacific and radioactive winds would carry devastation across continental United States. Lay down bombs along the line of the iron curtain and death would sweep over the U.S.S.R.

The marvelous development of artificial radioactive isotopes, so useful in medical, biological and industrial research, tells how hydrogen and atomic bombs can be used for such poisonous, radioactive warfare.

Around the bomb materials or mixed in with them would be placed large quantities of elements that would be transformed by neutrons into intensely radioactive substances. Everyone knows what some of these might be. Use cobalt metal and the air will be filled with the radium substitute now being used extensively in hospitals for irradiating cancers. This radiocobalt lasts a relatively long time, since only half of it is radiated away in five years. The debris of a cobalt-reinforced hydrogen bomb would persist for years, and its deadly dust would be carried around the earth by the atmospheric circulation, just as the dust of the explosion of Krakatau volcano in 1883 reddened sunsets of the world for years afterwards. Creating radiocobalt in this way would be a suicide operation, for the radioactivity would backfire in this way.

There are much shorter-lived radioisotopes, such as radioiodine made in

the atomic reactors by neutron bombardment. Iodine's radiations wear out much faster, since its half-life is only 13 days, but it is very intense at first. To an enemy population it would be a dangerous dose. It would bombard everything in the same way that, medically, it is now used to destroy and reduce the activity of the thyroid gland when it is overactive or cancerous.

Other artificially radioactive substances could be created in the hydrogen bomb blast. Some of them undoubtedly would be most effective for warfare.

Would our nation use such radioactive warfare? Would a potential enemy launch this new and insidious attack, just as the Germans started gas warfare in the First World War?

Against such radioactive poisons there seems to be little chance of real protection. It might wipe out life on the earth. Crops, animals, and all other living things would be affected. A fortunate few might be able to survive the attack by wearing protective clothing and masks to filter out the radioactive dust.

These are realities of the atomic dilemma that faces the world. In other nations, people and officials are asking the same questions with the same indecision and gnawing fear, so far as they are allowed to know the facts.

The Hydrogen Bomb

The major question about the hydrogen bomb is: Can it be made and will it explode as expected?

You may be confident that the hydrogen bomb is in about the same state that the uranium bomb was about 1943 or 1944, a year or two before the first atomic explosion. Scientists think it can be done and the Atomic Energy Commission is working on it. Undoubtedly the U.S.S.R. is working on it, too, and may even get there first.

The hydrogen bomb has not been made or exploded. That is a matter for coming months.

Fusion Process

The hydrogen or superbomb reaction is different from that of the atomic or A-bomb made of fissionable materials, uranium or plutonium. The energy comes from the changing of matter into energy, as Einstein computed, but the lightest elements known are involved in the "fusion" process of the superbomb.

The size of the fission or A-bomb is limited by the circumstance that if too much of the fissionable metals — uranium 235 or 233 or plutonium — are brought together they will explode because the neutrons from their exploding atoms will start and maintain a chain reaction. This critical mass is somewhere between 2.2 and 220 pounds, exactly what is a secret. The A-bomb is set off by bringing together suddenly two pieces of less than critical mass which together will be more than the amount that would start the explosion.

Instead of being self-starting, the superbomb needs the high-temperature "trigger" of a fission bomb to get it going. It is safe to bring large amounts of the raw material of the superbomb together — it can weigh a ton or more. Its size is limited only

by the amount of hydrogen "fuel" that can be "set fire" in the few billionths of a second of the explosion of the "igniting" A-bomb. The high temperature necessary to set off the superbomb can be provided by the tens of billions of degrees Centigrade of the A-bomb explosion.

The speed with which the hydrogen atoms can react under such great flash heat determines what can be used to make the superbomb.

Certainly the ordinary kind of single-weight hydrogen will not do, for it takes far, far too long. Computations show that such reactions, that keep the sun stoked with energy, extend over billions of years. Billionths of a second are more like what is necessary in the fusion superbomb.

Three Hydrogens

It is just as well that there are three kinds of hydrogen. The commonest is the ordinary sort in the waters of the earth. Its heart or nucleus consists of one proton. Then there is heavy hydrogen, or deuterium, which was discovered in America in 1931, naturally present as 1/4500th of hydrogen in nature. This is hydrogen 2, with a nucleus of one proton and one neutron, which as a particle is called a deuteron. Then there is tritium, the third kind of hydrogen, "heavy, heavy hydrogen," which has a nucleus of one proton and two neutrons, called a triton. A team of British physicists first made it in 1934 by atomic bombardment of deuterons with deuterons. It may be produced by neutron bombardment of lithium metal in an atomic reactor such as those at Hanford. It is still a very rare element, since it is radioactive and half of it disappears every 12 years. Yet this is a prime stuff of the superbomb to be.

The Sun's Process

What happens in the superbomb is that hydrogen is turned into helium. This is what happens, so far as an end result is concerned, in the atomic process that keeps the sun stoked. The transformation in the superbomb is different and direct. It is almost instantaneous and it will happen only when the hydrogen is concentrated and "ignited" by A-bomb heat.

It seems most likely that either a reaction of deuterium with tritium, or tritium with tritium, will be the reaction of choice. Deuterium combined with tritium gives a helium atom and a neutron, while two tritons coming together produce the helium atom (alpha particle) and two neutrons.

The heavier hydrogens are expensive, although the AEC price tags upon them now are not fair values of their cost in the superbomb production. (For research purposes it is possible to buy from the A.E.C. five cubic centimeters of 50% tritium gas at a cost of $1,315 which figures out to something like the fantastic figure of a quarter of a billion dollars per pound.) Deuterium can be concentrated out of ordinary water, but tritium must be made with the use of fissionable material, competing for neutrons with the production of plutonium which is the principal job of the big atomic reactors at Hanford, Wash. Tritium is made by neutron bombardment of the very light metal lithium, just as plutonium is made by

bombardment of uranium 238 by neutrons from the controlled fissioning of uranium or plutonium.

The heavier kinds of hydrogen would be put into the superbomb in as concentrated form as possible, which means that they must be under very great pressure or very cold or both. Or they may be used as solid compounds — this is speculation, but the uranium of the trigger bomb might be combined with the heavy hydrogens to form a solid.

The problems in making the superbomb seem very much more complex than the making of the original uranium bomb must have been. Of course, we know now that the fission (uranium or plutonium) bomb will go off. We are not so sure that the superbomb will explode the way that we expect it. What has been done is so much simpler than what has never been done.

Useful Only for Bombs

Except for the fear that others will do it first and use it against us, it would be foolish to try to make the hydrogen bomb. Even the making and stockpiling of tritium is a bad business as we shall lose half of our supply every 12 years, due to its radioactive disintegration.

Some scientists argue very strongly that we should not try to make the superbomb. Certainly it has no industrial or peacetime uses that can be foreseen now. Its reaction is just too big, sudden and powerful. There seems to be no way you can use the reaction in a power plant.

If it works, it is devastation beyond man's most hellish dreams.

Panic Danger

When an atomic bomb (A or H) pulverizes a city, in addition to thousands killed and wounded, many of the physically unharmed survivors will be damaged emotionally so that they are real casualties.

Only one out of five of the survivors will remain cool, collected and capable for carrying out any rescue or defense operations.

Some will run screaming through the debris-cluttered streets, crying hysterically. Others will be so paralyzed with fear that they will be unable to get out of bed, or do anything else. Experts estimate that such violent cases will number 5% to 10% of the survivors.

. Most of the living, unwounded population will be stunned and bewildered. They will be unaware of any emotion but show signs of intense anxiety. They will act automatically, like sleep-walkers. This will be the fate of 75%, and it is what happens in any major disaster, atomic or otherwise. These people are real casualties even if they appear to be relatively normal.

Few Cool Heads

The fate of the recovery of a bombed city will rest in the hands of the relatively few who are "cool heads." Through them, experts working on mental civilian defense against the atomic bomb hope to prevent panic and demoralization of the population when and if disaster comes.

What will happen after an atomic bomb attack can be predicted from what has happened in other disasters or on the battlefield.

Studies of military combat in World War II showed that only one out of every five soldiers actually fights. Most of the others stay on the battlefield but do not fire their weapons. They may work automatically in gun-crews but they do not fight individually.

Very much the same thing happens when civilians are forced by disaster into similar dangerous situations. This was shown by studies of Canadian disasters by Dr. J. S. Tyhurst, McGill University psychiatrist.

Warn of Real Dangers

Tell the people what dangers to expect. Tell them what fears are actually groundless. This is the best mental preparation for preventing panic and worse in any atomic disaster.

The government should develop the confidence of the people by explaining the situations, as they develop, that may bring danger. Psychologists, psychiatrists and public opinion experts advise that this is good mental preventive medicine.

Most important is a continued flow of reliable information that will prevent the spread of fear-inspired rumor. In time of atomic disaster, the people will turn to the sources of news that they have learned to rely on in the past. These news sources should continue to function, no matter what befalls a city or an area.

Groups should be organized in every neighborhood to act in an emergency. Persons have less tendency toward panic if they have behind them the solidarity of a group, especially if it is headed by a person they trust.

Alarming information, such as what is likely to happen in a bombing, is less dangerous to public morale if it can be discussed in a group. Some of a person's quite understandable anxiety can be dissipated by discussion with others and feeling that they are "all in the same boat."

Definite plans should be made for various emergencies. What should be done if the water supply is cut off? Suppose the electrical supply is stopped by disaster. What to do when there are no lights and no power? What about blocked roads and demoralized public transportation?

Just as doctors and hospitals must be ready to handle the bloody wounded with physical injuries, so there must be "mental first aid" stations to give treatment to those who will break under an atomic bombing and rush screaming through the streets.

Even now when repeated rumors of flying saucers almost panic our populace, the public needs treatment for its severe case of jitters. We must know what are the facts. What will happen when fanciful saucers are replaced by real atomic bombs, if that time ever comes?

Atomic Power Overdue

There should be atomic plants running now, to fulfill the hopeful predictions of five years ago made just after the world knew that atomic bombs had been exploded.

As it is, after several seeming false starts, we are probably two to three years away from the successful operation of the kind of atomic power plant that might run submarines several times around the world without refueling.

Our atomic power bets are laid almost exclusively upon two ship pro-

pulsion reactors, one reported to be in the advanced stages of engineering design and the other just begun. As an auxiliary to weapons development, there are other projects of the Atomic Energy Commission which will aid the eventual power use of uranium at the same time that they help build more and better bombs.

The military situation has dictated that virtually nothing be done in power development that does not contribute to our armed strength.

In the long run successful application of atomic power may not come any later due to this emphasis on fighting power. The problems in making a ship power plant are those of a stationary installation, with many conditions much more difficult. For one thing, the cost factor is thrown overboard, for a ship that does not have to refuel is priceless.

The cost of building an atomic ship reactor for the Navy is estimated as about $1,400 per kilowatt, which is about ten times as much as a conventional coal-burning power plant.

Intense Radiation

Intense radiation bombardment from the fissioning uranium or plutonium is the greatest difficulty in an atomic power plant. At least six feet of concrete is needed to shield the heat-producing reactor and make it safe for men and materials nearby.

Ordinary materials, such as steel and other common metals used in power plants, do not stand up under the battering of neutrons, intense gamma rays (X-rays) and electrons (beta rays). Heat in an atomic pile or reactor, where the fissioning is going on, reaches at least a million degrees. No ordinary structural materials can withstand such temperatures.

Almost everything battered by the radiations is made so radioactive itself that it becomes a source of dangerous radiations. Transfer of heat from the reactor to the engines involves handling so much liquid or gaseous "radium."

Heat Engines

So far as known, there must be used relatively conventional methods of applying the heat of atomic energy to practical engines. Somehow the heat must be brought to the state of the few hundreds of degrees of temperature range that steam or turbojet engines can use.

Production of electricity directly from the neutron impact or the fission reaction itself is not unthinkable, but there has been no hint of any progress. Years ago there were attempts at direct electrical production from the flame of ordinary combustion.

The experience in atomic reactors or piles has been with slow neutrons, the energy range that seems easiest to use. Faster moving neutrons can be used and two of the AEC reactors are pioneering in this unknown field. A materials testing reactor is designed for the highest neutron flux yet attempted but it is merely a step toward other reactors. The second ship propulsion reactor will operate in the unexplored intermediate neutron range. This is important because this intermediate range will also allow the production of more fissionable material, breeding it is called, than is fed into it.

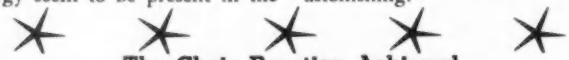
An atomic energy plant or reactor is an atomic bomb kept under control. There is always the hazard of a runaway reactor that would explode as a bomb or otherwise, although the safeguards are many.

Any sale of power stocks or postponement of power development plans anywhere in the world, in anticipation of practical atomic power, is no more justified now than it was at the end of the war.

Using the world's precious fissionable material to boil water or the equivalent for gross power production may be a very wasteful use of our natural resources of uranium (and thorium from which fissionable uranium 233 can be made).

Unexpected new sources of chemical energy seem to be present in the atomic reactors. For instance, potassium chloride when irradiated changes into potassium sulfate, which means that not only is chlorine changed to sulfur but that oxygen is added, which is a real chemical surprise. Such oxidation is usually obtained by burning fuel or using electricity. Such changes in chemical compounds may open new chemical doors and provide a way to use atomic energy without radiation dangers.

The many radioactive isotopes, also by-products of the atomic reactors, are considered by many to be as important as atomic power itself, because of the discoveries that can be made with them. Other chemical reactions of the atomic furnace may be even more astonishing.



The Chain-Reaction Achieved

➤ Our common sources of power, other than sunlight and water power, are chemical reactions—usually the combustion of coal or oil. They release energy as the result of rearrangements of the outer electronic structures of the atoms, the same kind of process that supplies energy to our bodies. Combustion is always self-propagating; thus lighting a fire with a match releases enough heat to ignite the neighboring fuel, which releases more heat which ignites more fuel, and so on. . . .Such a self-propagating reaction is called a "chain reaction" and such conditions must be achieved if the energy of the nuclear reactions with which we are concerned is to be put to large-scale use. . . .

A theory was advanced by H. Bethe to explain the heat of the sun by a cycle of nuclear changes involving carbon, hydrogen, nitrogen, and oxygen, leading eventually to the formation of helium. This theory is now generally accepted. The discovery of a few (n,2n) nuclear reactions (i.e., neutron-produced and neutron producing reactions) suggested that a self-multiplying chain reaction might be initiated under the right conditions . . . .The effects of neutron bombardment of uranium, the most complex element known, had been studied by some of the ablest physicists. The results were striking but confusing. The story of their gradual interpretation is intricate and highly technical, a fascinating tale of theory and experiment. —*Smyth Report.*

How We Learned About the Atom

The Structure of the Atom

by JOHN A. WHEELER

➤ IF SCIENCE can be called the human activity concerned with extending the range of our experience and reducing this experience to order then the study of the atom is science indeed. Nowhere, except perhaps in astronomy, has man gone further in exploring, by the aid of ingenious experiments, a domain of distances entirely outside the realm where he lives and moves, and nowhere has a logical structure more harmonious and beautiful been erected to bring into order the great range of experience so uncovered.

The science of the atom has advanced in three great waves and we are now in the midst of a fourth wave whose outcome we cannot predict. First was the period of the last century when evidence from chemistry, evidence about pressure and temperature relations of gases, evidence about the effect of electric currents on solutions, all forced the recognition of the existence of molecules and atoms. At the end of the first period the 92 atoms formed the starting point for any description of nature and these atoms were themselves regarded as elementary units.

The second period of advance extended from 1911 to 1928 and lead to the view that the atom itself is a complex system composed of a central nucleus and planetary electrons circulating about it. At the end of this period it proved possible to summarize in a few simple principles the laws of motion of these electrons and with the aid of these laws to give a satisfactory account of a most extensive range of physical experience.

Quantum Theory

The quantum theory of the atom accounted for the characteristic colors given off by the individual chemical elements in an electrical discharge and the chemical affinities of certain atoms for certain other atoms, for the stability of molecules, for the melting and boiling points of fluids and liquids, for the existence of metals and their electrical conductivity, and in fact, so far as mathematical difficulties did not supervene, for all the physical properties of ordinary matter as we know it.

At the end of this second period we recognized all atoms as systems of the same kind built up out of a fundamental unit, the electron, together with an exceedingly small nucleus. Only the electric charge on the nucleus had any significant effect on the properties of the atom, and the electric attraction of the nucleus determined how many electrons went in planetary orbits about it.

The third great period of advance extended from the discovery of the neutron by Chadwick in 1933 to the elucidation of the phenomenon of

fission of uranium in 1939. This period of advance began by recognizing as common building blocks of all nuclei, the newly discovered neutrons and the protons which occur in free form as nuclei of hydrogen atoms. To these two particles was given the common name of nucleon and to the science of their combination in stable arrangements and their rearrangement in collisions has been given the name of nucleonics. The explanation of the radioactivity of radium, the operation of a chain reacting pile and the explosion of an atomic bomb all form part of this science of nucleonics.

Nuclear Energy

This science is now comparable in its unity and comprehensiveness with the science of chemistry itself. Just as chemistry can predict, from the science of atomic structure, the energy which will be liberated when atoms combine to form molecules, so nucleonics can predict with a reasonable accuracy from the science of nuclear structure how much energy will be released by neutrons and protons in any given proportions combined to form a nucleus of any given size.

As important as the energy of a reaction is the probability it will take place. The rate of a reaction is no more important in chemistry than it is in nucleonics. In this science the likelihood that a bombardment of nucleus (b) by nucleus (a) will give rise to any chosen product is measured by an effective target area or cross section. A few simple principles suffice to predict these cross sections in a large number of cases of practical importance. These principles make it possible to see why it is very unlikely that any nuclear chain reaction can be developed on the earth which does not make use of neutrons and nuclear fisson. The same principles make it possible to see why in stars, under conditions of very high temperature, energy producing reactions take place which can be produced on earth only under laboratory conditions.

It was an amazing feature of the second and third periods of advance that the idea and problems of structure could be separated so cleanly from each other and that they yet had such a striking similarity. The nucleus looks to an electron one hundred times smaller than the sun looks to the earth and its internal structure is of even less importance to the electron than internal construction of the sun is to the earth in its orbit. Conversely, the motion of the neutrons and protons within the nucleus is affected to no noticeable extent by the motion of the planetary electrons in their far away orbits. Yet both the properties of the atomic system and the properties of the nucleus found their explanation in terms of one or two elementary particles. All of chemistry, all of the structure of the atom outside the nucleus, all of nucleonic physics itself required for their explanation only three particles: the electron, the proton, and the neutron.

Intermediate Particles

We are now in the midst of a fourth period of advance where we recognize not only that the neutrons and protons themselves are probably not elementary particles in the same

sense as the electron, but also where we are finding an increasing number of new particles which are intermediate in mass between the electron and the eighteen hundred times heavier nucleons and which do not fit in any now recognized way into our description of nature. In contrast to atomic physics and nucleonic physics the science of these new particles, their creation, their destruction and their transformations and relations to each other is sometimes called sub-nucleonic physics and sometimes elementary particle physics.

Electron Problem

The first one to make a clean division between nucleonic and sub-nucleonic physics was Heisenberg. It was he who in 1933 essentially proposed to exclude from the science of nucleonic physics those transformations in which electrons were observed to come out of atomic nuclei. He noted that a nucleus composed solely of neutrons and protons which forever preserved their character could never give out an electron. He therefore proposed to say that the process of emission of an electron from the nucleus was a process in which one of the neutrons transformed into a proton and an electron. The problem of such changes is evidently one of sub-nucleonic physics.

Other elementary particle transformations had been discovered the year before, in September 1932, by Anderson. He found a beam of electromagnetic radiation was able to create a pair of negative and positive electrons in the free space outside the atomic nucleus. Later observations showed that the positive electrons so observed were capable of annihilating the ordinary negatively charged electrons with the complete conversion of their mass into electromagnetic energy.

In 1938 Anderson and Nedermeyer, in the course of studies of cosmic ray particles, found evidence for a new particle, now called a meson, with a mass two hundred times as great as the mass of an electron or one-ninth as great as the mass of a proton or neutron. Recently Powell has found evidence of still another kind of meson with mass about twice as great as that of Anderson's meson. A few years ago Leprince Ringuet found one picture of a particle with a mass nine hundred times the mass of an electron. A communication by Rochester and Butler of the University of Manchester reports more evidence for a particle of mass about 900. Evidently the scheme of things is much more complicated or much simpler than we at first conceived.

Negative and Positive

More and more the possibility suggests itself to us that all the heavier particles are built up, in some way we do not now understand, out of positive and negative electrons. Moreover, a re-examination of older arguments that there can be no electrons in the nucleus leads to the conclusion that it has in fact no physical meaning to say that there are no electrons in such small domains. Any physical experiment designed to measure the number of electrons in the nucleus will automatically cause the creation

of an indeterminate number of pairs of negative and positive electrons which will be indistinguishable from the electrons which one seeks to observe.

Mesons in Orbits

The remarkable behavior of positive and negative electrons in domains as small as those of the nucleus lends a special interest to this branch of elementary particle physics and suggests that there may be hope in this direction to gain some insight into the structure of the other elementary particles.

Recent experimental and theoretical studies of the interaction of negatively charged mesons with atomic nuclei furnish another point of advance on the elementary particle problem. Such mesons are able to move in orbits around the atomic nucleus, which resemble the orbits of electrons in shape but are in size two hundred times smaller. Simple arguments about the energy released in the jumps of negative mesons from one of these orbits to another leads one to expect that these particles will be able to initiate a special type of fisson in uranium or heavier nuclei. Although experiments in this direction have not yet been performed, the theoretical evidence leads one to believe that in such a reaction the energy release will be about three hundred million electron volts—about 50 per cent more than the energy released in the usual type of fission process.

▶ JOHN ARCHIBALD WHEELER *was born in Jacksonville, Fla., in 1911. He studied under Niels Bohr at the Institute of Theoretical Physics at Copenhagen in 1934, after taking his Ph.D. at Johns Hopkins. He was drawn into the Atomic Energy program through the Hanford plant at Richland, Wash. He is now professor of physics at Princeton University. His field is the mechanism of nuclear fission and the structure and transformations of atomic nuclei and elementary particles. The address reprinted above, from* CHEMISTRY, *January 1948, was delivered at the Cooper Union Forum.*

Accelerators Transmute Elements According to Cross Section of Each

How Atomic Bombardment Works

From the Fifth Semi-annual Report of the Atomic Energy Commission.

➤ THE MOST EXTENSIVE field of nuclear data accumulation comprises the studies of what happens when the fundamental particles of the atom collide with one another or with the nuclei of varying forms (or isotopes) of the atoms of the elements so far identified. Finding these facts is the purpose of the research work done with particle accelerators — synchrotrons, cyclotrons, betatrons, Van de Graaff generators, and linear accelerators — and with nuclear reactors, or piles.

There is much immediate purpose to these studies. Through them the scientists are building the complete record of the nuclear reaction cross sections of more than 700 isotopes of the elements when each is struck by nuclear particles of varying energies, a description of great importance to the physicist and the engineer. For these technicians, the facts about nuclear reaction cross sections tell how and what materials to choose for the structural frame, the control rods, the cooling gases or liquids, and the shields of the nuclear reactors.

The term "cross section" is a very common one in nuclear science and engineering. It indicates to the physicist, chemist, metallurgist, or engineer working with nuclear reactors, the probability that a given nuclear reaction will take place. The cross section measures the size of the "bull's-eye" or nuclear target, which is an important factor in whether a "hit" or reaction occurs. But this is not the only factor; under similar conditions any one of several types of nuclear reactions may occur, each a definite percentage of the time. Scientists take care of this situation by assigning a cross-section value to each reaction. These values, which are determined experimentally, enable him to calculate the probable number of hits.

There are many types of nuclear reactions, such as an alpha-neutron reaction, a proton-neutron reaction, or a deuteron-neutron reaction. The symbol for an alpha particle is a; for a neutron n; for a proton p; and for a deuteron d. Thus, the three reactions mentioned would be written (a,n), (p,n), and (d,n). The first symbol represents the bombarding particle, the second, the emitted particle after the reaction has occurred.

For whatever purpose the scientists and engineers wish these data, the scientists must first collect them. The collection starts through the process of bombarding the nuclei of a target material with a beam of particles coming from one of the small or great machines of present-day nuclear research.

At present, the entities most useful for bombarding nuclei are protons, deuterons (hydrogen 2), tritium (hydrogen 3), helium 3, alpha particles (helium 4), gamma rays, mesons of several varieties, neutrons, and electrons. Since the type of nuclear reaction that occurs and the probability of its occurrence vary considerably with

the energy of the bombarding particle, it is necessary to work over a great range of energies, say from one-thousandth of an electron volt to several billion electron volts. Moreover, it is desirable for the energies of the bombarding particles in a given beam to be precisely known and to be monochromatic; i.e., all of the same energy. If the bombarding particle has a charge, the velocity or energy of the beam may be raised to any desired level by one of the various types of particle accelerators. The neutron is chargeless so that it cannot be accelerated by a particle accelerator.

However, high energy neutrons are most readily obtained by using a particle accelerator to bombard a suitable target material with a charged particle such as the proton, deuteron, or alpha particle. The neutrons are emitted from the reaction between the bombarding particles and the target.

The nuclear reactor provides an abundant source of low energy neutrons for neutron bombardment. This very important tool for modern physical research is available only at the research establishments of the national atomic energy program. No universities or industries possess such machines.

The Atomic Energy Commission has reactors now available for general research at the Oak Ridge National Laboratory and the Argonne National Laboratory. These facilities are open to men and women of industries and colleges and universities from any part of the country. Of course, much classified research of use in the development of the phases of the atomic energy program having to do with weapons and power production is carried on at these and at other reactors owned by the Commission as trustees for the American people.

Cyclotrons, synchrotrons, and betatrons are particle accelerators employing large electromagnets to hold the paths of the charged particles being accelerated in closed or spiral orbits. These machines contrast with linear accelerators and Van de Graaff generators which do not employ electromagnets. In the latter the paths of the particles are straight lines.

A brief tabulation of the various types of machines follows:

Particle Accelerating Machines

Type of Machine	Maximum Energy (MEV)	Precision of Energy Determination	Number of Particles
ELECTRON ACCELERATORS			
Betatron	300	Fair	Plentiful
Synchrotron	300	Fair	Plentiful
PROTON, DEUTERON, TRITIUM, HELIUM-3, ALPHA ACCELERATORS			
Van de Graff	12	Excellent	Plentiful
Cyclotron	20	Fair	Plentiful
Linear accelerator	32	Fair	Few
Synchrotron	350	Fair	Few
PROTON ACCELERATOR			
Proton synchrotron	10,000	Fair	Few

Energy Plays Essential Part In Transformations of Atoms

Birth of Matter

by GLENN T. SEABORG

➤ NUCLEAR SCIENCE is about to enter, and in fact has to some extent already entered, an important new phase in its development, namely, the area of ultra high energies. A limited entree into this region has already been permitted through observations with high energy cosmic rays, but these are of such low intensity as to limit seriously both the rate and the scope of progress which is possible. New ideas for design, together with new techniques for building, have led to prospects for the construction in the rather immediate future of a number of machines capable of accelerating electrons and light positive ions to an energy region comparable with that of the most interesting of the cosmic rays.

This new phase is coming right on the heels of the amazing atomic energy development, which began with the discovery of the nuclear fission reaction in uranium by O. Hahn and F. Strassmann in 1939 and culminated in the successful attainment of the self-sustaining nuclear chain-reaction and the manufacture in quantity of the synthetic element plutonium for application to this purpose.

The nuclear chain-reaction is notable for the amount of energy which can be developed, since substantial quantities of fissionable material can be made to react and hence convert mass to energy. Since this is done through the medium of neutrons, another important feature is the intensity and total quantity of neutrons which have become available, leading to the transmutation of elements in macroscopic amounts and the production of radioactive isotopes on a heretofore undreamed of scale.

It is possible, and in fact quite probable, that the coming step into the very high energy region will lead to developments different in principle, in that it will go beyond the rearrangement of nuclear particles and enter the area of important insight into interactions between and the internal transformations of the fundamental nuclear particles themselves. Of course, even in the reactions which may be termed simple rearrangements of the fundamental constituents of nuclei, there will be important differences from previous observations which will be peculiar to the high energies involved.

Nuclear Science Young

While we are standing on the threshold of this new adventure, it is interesting to recall that the first induced nuclear transformation was observed by Rutherford only about thirty years ago. It was in 1919 at the famous Cavendish Laboratory in England that the bombardment of nitrogen with alpha-particles led to the cloud chamber observation of its

transmutation to oxygen with the emission of protons. The source of alpha-particles in this case was one of the natural radioactive elements; and, in fact, it was not until more than a decade later, in 1932, that the first nuclear transmutation by totally artificial means was effected.

In this now famous classic experiment the British scientists J. D. Cockcroft and E. T. S. Walton accelerated protons to an energy of about 0.5 Mev by a direct fall through a potential difference of this magnitude. These protons were used to bombard the light element lithium. With the help of a cloud chamber the observation of the transmutation to two alpha-particles was made.

Acceleration Machines

Although many of the first acceleration machines were of the type in which the total accelerating voltage was simply a high voltage applied once, such as the A. C. rectification and voltage multiplier units and the electrostatic generator, the principle of resonance acceleration in which a particle is subjected to a small accelerating field applied repeatedly over a long path, was being developed simultaneously. This found its most practical application in the magnetic resonance accelerator or cyclotron developed by E. O. Lawrence at the University of California. This instrument was widely used in the 1930's and even the early models continue to yield important results.

The new machines all are characterized by the application of this resonance principle and in fact are also characterized by the application of less high voltage and more brain power than has been the case for the machines of the past.

The acceleration machines in the past, and also the chain-reacting piles, have given rise to bombarding particles with energies in the range of millions of electron volts, extending in a few cases into the region of tens of millions of electron volts. This energy region is, roughly speaking, just that of the nuclear binding energies, that is, the energy of binding of the elementary and small particles such as the neutrons, protons, and alpha-particles. The transformations have therefore been characterized by the addition or subtraction of one or two such particles leading to changes of something like one or two units in the atomic number and mass number of the bombarded material.

New Energy Range

Although it is of course an arbitrary matter as to when we may consider ourselves to have entered a new energy range, it is generally considered that this is the case as we go into the region of hundreds of millions of electron volts. Although we have as one reason for this simply the historical fact that because of the course which the development of accelerators has taken, this energy region is being entered by making a large jump, of the order of a factor of ten or more, essentially all in one step, we have in addition a more scientific reason for singling out this area.

Creation of Mesons

It seems reasonable to expect that it will be in this region that a first step in the inter-conversion of the elementary nuclear particles might take place. It may be possible with such energies to create mesotrons in quantity by artificial means. The mesotron, which has been observed and studied for about ten years as an important constituent of the cosmic rays, seems to have a rest mass of some 200 times that of the electron and hence the energy equivalent of its mass is about 100 Mev. Thus, it might be expected that with the acceleration of particles to a kinetic energy above 100 Mev, a transformation of kinetic energy might occur with its appearance as mass in the form of the mesotron.

Actually there are some experimental, together with a number of theoretical, considerations which lead to the view that this transformation, in order to occur with any significant probability, must involve the creation of a pair of mesotrons, one negatively and the other positively charged, and thus a minimum of 200 Mev of kinetic energy will be needed. This amount must be further increased in order to allow a sufficient amount of kinetic energy to go into the products and other participants of the transformation so that the laws of conservation of momentum may be obeyed, and therefore, depending upon the particular reactions involved, the actual threshold may be somewhere above 200 Mev. (Known examples of transformations of the type in which elementary particles change their character or are created or destroyed are the processes of "pair production" in which positron-electron pairs are created from gamma-rays and "annihilation" in which gamma-rays are produced from positron- electron pairs.)

The mesotron plays an important role in the current theories of nuclear structure in that it is supposed to be intimately involved in the very fundamental interaction between neutrons and protons through which they are held together to create a nucleus. It is therefore hoped that their study as a result of their production in quantity by artificial means might give just the key which is needed to the fundamental understanding of the nucleus of the atom.

Although the accelerators for the region of hundreds of millions of electron volts all use the resonance principle, there are a number of different methods by which this is done, and thus we have a number of devices such as the synchro-cyclotron, the betatron, the synchrotron, and the linear accelerator.

Chemical Identification

Before proceeding to a consideration of the actual results which have been attained through the use of the machines already in operation, it may be well to say a few words concerning the role which the chemist plays in this work. One of the most powerful means of determining a nuclear reaction is to identify chemically the radioactive products of the reaction. After the machines have effected the transmutations, the chemist goes to

work, and he finds himself faced with some extremely interesting and challenging problems. It is his task to identify the atomic number of the transmutation products and his services here are practically indispensable. Usually there are a great number of radioactive isotopes of many elements produced during the irradiation of the target material.

Wide Range of Isotopes

The results with the 184-inch cyclotron have been spectacular. The bombardment of elements anywhere in the periodic table with 200 Mev deuterons or 400 Mev helium ions gives rise in each case to a tremendous number of radioactive product isotopes often extending over an atomic number range of ten or fifteen or twenty. For each of these elements in turn there are produced a number of radioactive isotopes so that in each bombardment the number of transmutation products is truly large. This leads to great complexity and a great strain is placed upon the chemical and physical measurements needed in order to unravel the results from each bombardment.

Already a number of results have been obtained of which it will be possible here to cite only a few. H. H. Hopkins and B. B. Cunningham have found among the many products from the bombardment of arsenic with 400 Mev helium ions the 37-minute Cl^{38} isotope. This corresponds to a reduction of 16 atomic number units, as the atomic number of chlorine is 17 while that of arsenic is 33; the corresponding decrease in mass units is 37. In another example, D. R. Miller and R. C. Thompson have found among the products of the irradiation of copper with 200 Mev deuterons and 400 Mev helium ions, in the manganese fraction alone, a range of radioactive isotopes from mass number 51 up to 56. M. Lindner and I. Perlman find that the bombardment of antimony (atomic number 51) with 200 Mev deuterons gives rise to radioactive isotopes extending from molybdenum (atomic number 42) to tellurium (atomic number 52) and the observations are still far from complete. These results, chosen quite at random, are meant to be only illustrative of the scope of the reactions which occur.

Writing the Reactions

The occurrence of nuclear reactions involving the ejection of so many particles has raised a question as to the method for writing the reactions. The ordinary nomenclature is inadequate because in many cases the path by which the final product is obtained is indeterminate. For example, in the production of 46-minute Mn^{51} from helium ions on copper, it is not known whether the reaction is due primarily to the direct ejection of (assuming the isotope Cu^{65} is involved) 6 protons and 12 neutrons or 3 alpha-particles and 6 neutrons or 5 protons and 13 neutrons to form an Fe^{51} which goes to Mn^{51} by positron emission, etc.; probably a combination of several of these paths is involved. Consequently we have adopted the convention of writing the reaction Cu^{65} (a,6z18a) Mn^{51}, in which

the z and a correspond to the loss in charge and mass units, respectively. According to this convention, for example, the above-mentioned production of Cl^{38} would be written As^{73} (*a*, 18z39a)Cl^{38}.

Spallation Reactions

It has also become convenient to have a term by which to refer to these reactions in order to distinguish them from ordinary nuclear reactions in which only one or two particles are ejected and from the nuclear fission reaction, and we have been using the term "spallation" reaction. Thus it can be seen that in the ultra high energy region the rearrangements of the constituents of nuclei lead to an astonishing richness of phenomena.

P. R. O'Connor has bombarded ordinary uranium with the 400 Mev helium ions and has found a tremendous number of radioactive products. These seem to extend, so far as can be deduced from the incomplete experiments, continuously from the region of uranium down to and through the normal region of the fission product isotopes and on below. Possibly the isotopes in the region between uranium and the rare earths are formed by the spallation reactions and the isotopes with atomic number below this are formed by the fission type of reaction.

Another observation of great interest is that of I. Perlman, R. H. Goeckerman, D. H. Templeton, and J. J. Howland who have observed that a number of elements well below the thorium-uranium region undergo the famous nuclear fission reaction when subjected to bombardments with very high energy particles.

They have observed that bismuth and lead undergo fission when irradiated with the 100 Mev neutrons which are produced in high yield when the 200 Mev deuterons impinge on any of the elements. The direct bombardment with 200 Mev deuterons leads to the observation of the fission reaction in bismuth, lead, and thallium; and with 400 Mev helium ions they have observed this interesting reaction with, in addition to these three elements, platinum (atomic number 78) and even so far down the periodic scale as tantalum (atomic number 73).

New Kind of Fission

The threshold for this reaction, determined for the case of bismuth, is in the neighborhood of 50 Mev energy. For these elements the fission process is characterized by a distribution of the radioactive fission product isotopes leading to essentially one broad peak in the distribution-yield curve rather than the characteristic two peaks with a pronounced minimum between them in the curve for the fission products produced in the slow neutron irradiation of uranium and plutonium. This fission product distribution extends to lighter elements as might be expected in view of the lighter mass of these elements as compared with uranium and plutonium.

It should be emphasized that this observation of the fission reaction in relatively common elements such as

lead opens no possibility for the production of self-sustaining nuclear chain reactions with these elements and there is no possibility for their employment as sources of atomic energy. One reason for this stems from the fact that any secondary emitted particles which might conceivably be eligible for perpetuating such a chain reaction have much too small an energy to be able to do so. However, this reaction serves to give us another look at the ways in which nuclear constituents can rearrange themselves and is of great interest from this point of view.

It seems highly probable that as a result of these new types of reactions the number of induced radioactivities, which already stands above five hundred, will be further increased by at least a hundred new isotopes. In the case of the spallation reactions many neutron deficient isotopes are formed thus making it possible to enter the region of the positron emitters in much the same way that the fission product isotopes have widened the area of the negative beta-particle emitters. It is probable that several of these new isotopes may become important as tracers. . . .

Creation of Matter

When it is possible to accelerate particles to the energy region of billions of electron volts, it may be possible to use this kinetic energy to synthesize neutrons and protons and thus truly to create matter from energy.

The rest mass energy equivalent of the neutron or proton is about one Bev (billion electron volts). Since these particles might be born in pairs, for example a pair consisting of a positive and a negative proton, and since a considerable fraction of the kinetic energy must be consumed in the process of momentum conservation according to the relativistic mechanics of the collision process, it follows that the threshold for such events will lie in the region of several Bev.

Another new process which might occur in the Bev energy region is that of the sudden production of many mesotrons in a single act, a phenomenon known to be brought about by single high energy cosmic ray particles and of considerable importance because of the light that it might throw on the whole theory of nuclear structure.

➤ GLENN THEODORE SEABORG *was born in Ishpeming, Mich., in 1912. He was teaching at the University of California when he was borrowed by the Metallurgical Laboratory of the University of Chicago from 1942 to 1946 for work on the chemistry of fissionable elements. In co-operation with associates at California he has created transuranium elements 94 through 98. The foregoing paper, given at a general assembly of the American Chemical Society in New York, is reprinted from* CHEMISTRY, *Nov. 1947.*

Exchange Force Holds Charged Atomic Particles Together

Neutron-Proton Exchange

by Ernest O. Lawrence

➤ The total energy of a heavy atom like lead or uranium is about two hundred billion electron volts. Therefore, studies of energy transformations over a vast range are of importance for a deeper understanding of atomic phenomena. In ordinary nuclear reactions involving only a few nuclear particles, such as the radioactive transformations or the transmutation of one element into its neighbor, the energy changes are only a few million electron volts. To be sure, in cosmic ray investigations fragmentary evidence of transformations of very much higher values have been obtained, but the discovery of atomic fission marked the real beginning of high energy physics in the laboratory.

Long before the discovery of fission the vast extent of nuclear energies was of course appreciated—and likewise the importance of producing ever higher energy particles in the laboratory. And so, almost ten years ago plans were laid to build a giant cyclotron—one as large as practicable both financially[1] and otherwise—with the hope that such a great instrument would produce particles of the next higher energy range—hundreds rather than tens of millions of electron volts.

The actual construction of the great cyclotron, with magnet pole pieces 184 inches in diameter and weighing more than 4000 tons, was well started when the war necessarily interrupted the work.[2] Now from the standpoint of the purely scientific objective of getting on with the job of exploring farther into the realm of the atom, the war interruption might have been a serious loss—a delay of some five years. Actually, this delay turned out to be a blessing in disguise for the wide experience gained in the war effort by the scientists and engineers concerned, as well as many new technological developments, contributed greatly to the rapid and successful carrying out of the undertaking. Moreover, my colleague Dr. Edwin McMillan and independently V. Veksler in Russia meanwhile elucidated the principle of phase stability in the multiple acceleration of particles, embodied in the synchrotron. They pointed out with such clarity and so convincingly the way to higher energies that immediately after the war when the 184 inch program was resumed, the

[1] The undertaking was made possible by the generous support of the Rockefeller Foundation, the Research Corporation and the John and Mary Markle Foundation. Since the war the project has been supported by the Manhattan District and the Atomic Energy Commission.

[2] However, as is well known, the 184-inch cyclotron magnet was finished and served a useful purpose in the war effort in providing a splendid laboratory facility for the development of the calutron, i.e. the electro-magnetic process for the separation of the uranium isotopes.

great instrument was redesigned, following their ideas, as a synchro-cyclotron, thereby more than doubling the power of the great accelerator. In the long view, therefore, and indeed in the light of new discoveries already made with these high energy particles, one may say that the delay of the war years will soon be made up, if it has not been already, by the more rapid progress in the accumulation of knowledge of atomic phenomena afforded by the availability of these higher energy particles in the laboratory.

The 184 inch synchro-cyclotron was turned on for the first time on November 1, 1946 and since that time has been producing deuterons of energies up to 200 million electron volts (Mev) and alpha particles up to 400 Mev. Since nowadays cyclotrons are in such wide use and, indeed, since so many synchro-cyclotrons are planned or are under construction in various laboratories in this country and abroad, it is hardly necessary for me to undertake a general description of these machines here.

I should like now to give a brief account of some recent investigations that have been carried out with this most powerful of atom smashers—for, indeed, as we shall see, particles of hundreds of millions of electron volts do a very thorough job of breaking up even the heaviest of the elements!

Beam of Neutrons

When the 184 inch instrument was first turned on—indeed, during the first evening of operation—a sharply defined beam of penetrating radiation was observed from the probe target in the cyclotron chamber. This extraordinarily interesting phenomenon of course was immediately the subject of some preliminary exploratory experiments. First of all, measurements of the penetrating power of the radiation were made by interposing various thicknesses of different materials in the path of the beam and observing the resulting reduction in intensity of the radiation as indicated by an ionization chamber. In this way Moyer, Hildebrand, Knable, Parmley and York found that it takes almost a foot of lead or concrete to reduce the radiation to one half—which indeed was something new in the laboratory!

Shielding Problem

Now, incidentally, apart from the scientific interest, the great penetrating power of these rays raised an immediate and urgent practical laboratory health problem, i.e. the provision of adequate radiation protection, for it was quite obvious that if the cyclotron were to be operated at full power for extended periods of time radiation shielding would have to be of massive proportions. In fact, on the basis of these and many later measurements it was determined that a concrete wall ten feet thick surrounding the cyclotron would be required for present levels of operation.[3]

These early observations also showed that the beam was made up largely of neutrons because lead was not

[3] It will doubtless be necessary to provide additional shielding when the synchro-cyclotron is modified to produce 350 Mev protons and larger currents of deuterons.

as effective per unit mass as water or concrete in absorbing the radiation. Furthermore, reasonably good estimates of the energy of the neutrons could be made from the absorption coefficients and on this basis it was concluded that their average kinetic energy was of the order of 100 Mev. That the neutrons were of such high energy was also established during those first few days of operation of the cyclotron by Wilson Powell who placed a cloud chamber in the beam and observed great numbers of high energy recoil protons—many up to 100 Mev and a few in the neighborhood of 200 Mev.

Beam of Neutrons

And so, there could be no doubt as to the general character of the penetrating radiation. Here was truly a remarkable beam of high energy neutrons. As you can well imagine, before settling down to careful quantitative investigations, all concerned could not resist the urge of curiosity to carry out numerous quick and easy qualitative experiments to observe some of the properties of the radiation. For example, various substances were placed in the beam and a glimpse of some of the resulting nuclear reactions was obtained by the observation of the induced radioactivities. In this way, for instance, it was discovered that these high energy neutrons produce fission in a number of heavy elements including lead and bismuth. Another interesting and immediately useful observation was the production of radioactive carbon in graphite disks placed in the beam. This reaction, C^{12} (n, 2n) C^{11}, has a threshold of about 20 Mev and, therefore, serves as a convenient detector of high energy neutrons.[4]

By placing small discs of graphite across the beam and measuring the induced activity Helmholtz, McMillan and Sewell were able easily to map out the shape of the beam with considerable precision. They established that the neutron's rays were largely confined to an angular spread of about ten degrees in the direction of the 200 Mev deuterons striking the cyclotron target. This interesting result was not unexpected, as will be seen in the following.

Splitting the Deuteron

A deuteron consists of a neutron and a proton held together with a binding energy of about 2 Mev which is quite negligible in comparison to the kinetic energy of the deuterons striking the cyclotron target. Thus, in effect, the collision of a 200 Mev deuteron with an atomic nucleus would be much the same as the simultaneous collision of a 100 Mev neutron and a 100 Mev proton. In other words, the particles are held together so loosely in the deuteron that in a nuclear collision they are "on their own," so to speak. With these considerations in mind it is easy to see that sometimes in a collision, the proton might just scrape a nucleus while the neutron would miss it altogether, thus, in view of the loose binding, proceeding on its way in a straight line with

[4] Recent experiments indicate that well above the threshold value the induced radioactivity is insensitive to the energy of the neutrons and therefore proportional to the flux.

the velocity it had at the instant of the collision. According to Professor R. Serber this is without doubt the process responsible for the observed beam of high energy neutrons.

Serber has worked out in detail the expected angular distribution of the neutron beam produced in this way. He pointed out that the neutron and proton in the deuteron in effect are not at rest relative to their center of gravity but have essentially a vibrational energy of some 2 Mev. In quantum mechanical terms one would say that the particles have "an intrinsic uncertainty in momentum" while in old-fashioned mechanical terms one would describe the deuteron as made of two heavy balls (neutron and proton) oscillating back and forth, held together by an elastic spring. Therefore, according to Serber, the expected distribution of velocities of the neutrons released on collision of the deuterons in the target would be given simply by adding their intrinsic velocity distribution to the velocity of the deuteron as a whole at the instant of collision. Calculations made in this way gave a theoretical distribution in excellent agreement with the experimental observations.

A Beam of Protons

Now, on the other hand, if in a nuclear collision the neutron of the deuteron just hits the nucleus, the proton will proceed on with the velocity it had at the instant of the impact and so a beam of protons would also be expected from the cyclotron target. Such charged particles, of course, would not proceed out from the target in a straight line like the neutrons, for they would be bent in the cyclotron magnetic field in circles half the diameter of the circles of the target deuterons. Thus, it was expected that protons would be observed bent to the central region of the cyclotron with energies in the range of 100 Mev and, needless to say, they were immediately observed.

The distribution in velocities of these protons, which we see according to Serber's ideas would be the same as for the neutrons, have recently been investigated by Chupp, Gardner and Taylor. They placed both photographic plates and disks of graphite with suitable shielding and diaphragms in the central region of the cyclotron and by counts of proton tracks in the plates, as well as by the radio-activity induced in the graphite by the reaction, C^{12} (p, pn) C^{11}, they obtained excellent agreement with Serber's theory.

And so, in this simplest case of atom splitting, theory and experiment are in excellent agreement. The phenomenon seems to be well understood.

Charge Exchange

I should like now to turn attention to the fundamental problem of the interaction of neutrons and protons. This is indeed a fundamental problem; for an understanding of this simplest of nuclear interactions must surely precede any general theory of nuclear matter.

Our present knowledge of nuclear forces is based very largely on the results of scattering experiments in the region of a few million electron

volts.[5] However, some years ago Heisenberg proposed the idea of charge exchange in the interaction of protons and neutrons to explain the constancy of the binding energy of particles in light and heavy nuclei. The low energy scattering experiments gave no evidence one way or the other on the reality of such a charge exchange phenomenon, but, nevertheless, for some time now it has appeared probable that there may be two types of forces between the nuclear particles, (A) ordinary forces and (B) exchange forces.

Like Billiard Balls

The former are not unlike the forces in billiard ball collisions (or Rutherford scattering) and in a sense are understandable in terms of older ideas. But the exchange force is essentially a new concept. This force arises from a charge exchange phenomenon. To put the matter in concrete terms, the charge exchange hypothesis means that when a neutron and proton collide, even just barely "touch" each other, the protonic charge oscillates back and forth between the particles, so that when the particles move apart after the collision there is a likelihood that the neutron will have acquired the charge, therefore turning into a proton while the proton will have become a neutron.

[5] Professor Gregory Breit, for example, was the first to work out in detail the expected neutron proton scattering on the assumption of a finite range of the forces and also the analysis of proton proton scattering data in the range of a few million electron volts.

The first truly convincing experimental evidence for the reality of this charge exchange between particles was given by the observation of Moyer and co-workers on transition effects in the walls of the ionization chambers used in the early measurements of the beam of high energy neutrons. They observed that the 100 Mev neutrons produced an abundance of correspondingly high energy recoil protons—quite in accord with the idea of the neutrons just touching protons in hydrogenous material and exchanging charge, thereby turning into high energy protons.

This important matter has, needless to say, continued to be vigorously investigated. Thus, in order to gain more quantitative information, J. Hadley, C. E. Leith and H. York have observed the secondary protons from carbon and paraffin. They used proportional counters in quadruple coincidence as a proton detector and by suitable absorbers between the counters were able to select the higher energy particles. They found that the most probable direction of a high energy proton ejected from hydrogenous material by a 100 Mev neutron is in the forward direction which is in accord with the charge exchange idea.

These observations leave little doubt about the reality of the exchange process but they do not rule out the possibility of part of the interactions of these high energy neutrons and protons being of the ordinary billiard ball type. In random collisions of billiard balls the chance of a dead center knock on wherein the recoiling ball

takes the whole energy of the cue ball is the same as one in which the cue ball just nicks the struck ball, the former proceeding on with little loss of energy and the latter moving sideways with relatively little energy. And so, the ordinary forces in neutron proton collisions would give rise to large numbers of recoil protons of low velocity moving almost at right angles to the neutron beam.

To look into this question Wilson Powell and Walter Hartsough have been using the cloud chamber which is best suited for the observation of low energy recoil particles. They find in confirmation of the observations of Hadley, Leith and York that there is a preponderance of high energy protons in the forward direction but in addition there are more low energy particles recoiling at large angles to the beam than would be expected on the basis of the charge exchange hypothesis.

Thus, we are led to the conclusion that both ordinary and exchange forces are necessary to describe the interaction of neutrons and protons. The experimental data along this line should soon provide much food for thought for our theoretical confreres!

Stars

One might infer from the foregoing that thus far the experimental observations into these higher energy levels of nuclear phenomena have been simple, orderly and understandable. Actually, of course, this is by no means the case as many new phenomena have been observed which are not understood and await further investigation. To illustrate, there are the star disintegrations that have occasionally been observed in the cosmic rays and which now are a common feature of the cloud chamber pictures in our laboratory. Thus, one interesting example is that of a star disintegration wherein a 107 Mev neutron apparently hit an oxygen nucleus splitting it into four alpha particles, the neutron bouncing backwards with some 70 Mev energy. Such an event, according to our present understanding, is rather improbable. Is energy and momentum really conserved in such individual nuclear collisions? Some day perhaps we shall know the answer.

New Isotopes

Professors Seaborg and Pearlman and their associates in chemistry were naturally curious as to the radioactive isotopes that would be produced by the high energy particles and so they made quick "spot checks" of the activities produced in various bombarded targets. They were confronted with a delightfully bewildering complex of radioactivities for it appeared that practically every chemical extraction showed several decay periods. With their extensive background and experience in the field, they were able to proceed rapidly in the identification of a large number of activities, some of which indicating that more than twenty nuclear particles had been knocked out. They soon found many new radio-active isotopes and in addition they were able to establish certain interesting general features of the nuclear reactions concerned.

It appears that more than one hun-

dred new radioactive isotopes will eventually be identified; and apart from their intrinsic scientific interest, no doubt they will soon find their usefulness as tracers in other fields.

Heavy Elements Fissioned

It was natural also at an early date to bombard the heavy elements and determine whether imparting these higher energies to the nuclei would result in fission. Again, the observations were interesting to the point of bewilderment, as bombarding elements such as uranium, bismuth and lead produced not only what were evidently fission products but also a great many other radioisotopes over almost the whole periodic table. In consequence studies along this line are only well started. However, some interesting new features of the fission process have already emerged, especially the radically different distribution of the fission products. Again, we must look to the future and to our theoretical colleagues for the meaning of these interesting observations.

Higher Energy Particles

Thus, we see that the production in the laboratory of accelerated particles in the 100 Mev range has opened up a rich domain for investigation. Perhaps, therefore, we should now be content to devote all our attention to the experimental attack on the problems in this field. But the very richness of the atomic phenomena already apparent in the 100 Mev level surely beckons us on to greener pastures—the domain of billions of electron volts!

It is, therefore, understandable that as soon as the synchro-cyclotron was well launched on its operating career W. M. Brobeck, who was chiefly responsible for the engineering design of the great machine, should give some thought to the next step up the energy scale. It did not take him long to reach the conclusion that it was well within the realm of practical feasibility to construct a great proton accelerator for the 10 billion electron volt level.

➤ Ernest Orlando Lawrence *was born in Canton, S. Dak., in 1901. After taking his Ph.D. at Yale and teaching there for several years he went to the University of California, where he has been professor of physics and director of the Radiation Laboratory since 1936. He is the inventor of the cyclotron and an authority on atomic transmutation. The above paper is part of his Silliman Lecture at Yale's celebration of the hundredth anniversary of the founding of its Sheffield Scientific School. It is reprinted from the Nov. 1947* Chemistry.

Meson Creation Experiments Throw Light on Atom Structure

Mesons Created in the Cyclotron

➤ EXPLANATION of the role of mesons, also known as mesotrons, in atomic rearrangements was made in a report by the United States Atomic Energy Commission, commenting on the artificial production of these particles in the cyclotron at the University of California. Dr. Eugene Gardner of the Radiation Laboratory there, with Dr. Cesare M. G. Lattes of the University of Sao Paulo, Brazil, at California on a Rockefeller Foundation fellowship, perfected the method of getting mesotrons from atomic nuclei by bombardment of suitable elements with the cyclotron's alpha particle beam at very high energies. Quantities of meson tracks were found on the photographic plates used to record the results.

Previous study of mesons had been largely confined to fortuitous occurrence of their tracks in cosmic ray records. Dr. Lattes, before coming to California, worked with a group of scientists from the University of Bristol, England, who visited the peaks of high mountains in the Andes to study cosmic radiation.

During years of careful study and development of special techniques, the scientists at Bristol, taking their emulsions to mountain tops in the Andes and Pyrenees, were able to explain how the light meson often originated from a heavier meson.

The Bristol scientists found on their photographic emulsions mesons of a mass of about 320 times that of the electron. They found that these heavy mesons were both positively and negatively charged, and there was some evidence that neutral mesons also existed.

All of these heavy mesons were studied at very low energies, of a few million electron volts, when they were close to or undergoing disintegration. At these energies, the positively charged heavy mesons, being unable to penetrate the electrical barriers of positively charged nuclei, simply wandered through the photographic emulsion until they disintegrated, giving birth to light mesons.

However, the negatively charged heavy mesons were greedily swallowed by nuclei, resulting in the detonation of the capturing nuclei into showers of particles called "stars." At the end of their course, when nearing capture, the mesons made a wavy track. The wavy track is made because the particle is relatively light, and, at the extremely low energies involved, it takes a severe buffeting from nuclei in the emulsion.

Thus the Bristol experiments explained where the light mesons originated and why they were unable to interact with nuclei.

The negative heavy mesons, known

as a result of the Berkeley research to have a mass of 313, are the type produced in the giant Berkeley cyclotron. The characteristic wavy track and the "stars" resulting from the detonation of nuclei are also observed. About half the meson tracks observed end in "stars."

The mesons were made by placing targets of carbon, beryllium, copper or uranium in front of the alpha particle beam. The negative heavy mesons emitted as a result of nuclear collisions are deflected out by the cyclotron's magnetic field, in a semi-circle away from the regular path of the positively charged alpha particles in the magnetic field.

With protective strips of copper on three sides to keep neutrons and other particles from entering the emulsion, the mesons are nicely separated from other radiations which would otherwise tend to obscure the newly observed phenomena. This experimental arrangement was devised by Dr. Edwin M. McMillan, Professor of Physics. Dr. Robert R. Serber, in charge of theoretical work in the Radiation Laboratory, joined in interpretation of the results.

Drs. Gardner, Lattes and Serber explained that mesons are actually produced by an intricate sub-nuclear process, which can occur at the peak energy of the giant cyclotron only a small percentage of the time in a given number of collisions. The explanation is something as follows:

An alpha particle is composed of four particles—two neutrons and two protons. On the average, each of these four particles has one-fourth of the 380 million electron volts which the cyclotron gives to the alpha particle, just as the total energy of a fast traveling train is divided up among its engine and different cars.

This equal division of energy is just an average over a given period of time. At times, the engine, or one or more of the cars, by the interaction of forces between all the parts, receives more than its share of available energy.

The same thing, in a very rough sense, occurs in the alpha particle. Therefore, sometimes when an alpha particle crashes into its target, one of the protons or neutrons has a great deal more than its average one-fourth share of the total 380 million electron volts. A small percentage of the time one particle will have as much as 225 million electron volts.

Head-on Collision

The particles in target nuclei are actually always in motion inside these nuclei. If a proton in a target nucleus happens to be moving toward a bombarding 225 million electron volt proton from the alpha particle at the time of a collision, there is a compounding of energy, the total of which is about 390 million electron volts, just sufficient for the release of mesons.

When two such protons meet head-on one of the protons is converted, by nuclear exchange forces operating at the time of collision, into a neutron and a negative meson.

The observed mesons have an energy of only about four million electron volts, an extremely low energy

for a meson. The mesons travel about nine inches in a vacuum between their origin in the target and their destination in the photographic emulsion.

The emulsions are about two-thousandths of an inch thick. They are very much like those of ordinary fine-grained photographic plates but considerably thicker. Stacks of about six emulsion plates are placed edgewise to the path of the mesons for 10 minutes. The mesons make a track about four one-hundredths of an inch long the track being made by electrons knocked off of nuclei in the emulsions. Scientists place the developed emulsions under a 600-power microscope in order to bring the tracks into view.

Mesons Made Earlier

Dr. Serber said that theoretical calculations have indicated that the mesons were being made from the beginning of operation of the big cyclotron. However, since barely enough energy was available and the percentage of meson-producing hits was so small, it was considered a strong possibility that mesons might not be observed at all until an even more powerful atom-smasher was built.

However, the compounding of the techniques developed by Drs. Gardner and Lattes permitted the observation of meson tracks on the first plates exposed in the cyclotron bombardments.

Dr. Lattes said that in British experiments with nature as a laboratory, eight people work a year to get 100 negative meson tracks. At the University of California, one person has observed 27 tracks in 10 minutes of observation.

The first plate exposed by Drs. Lattes and Gardner, for a period of thirty seconds, yielded 100 times as many mesons per plate as were obtained in the Andes in 45 days. Thus ten million times as many mesons per second were detected in the cyclotron as on a mountain top.

The scientists have placed emulsions inside the cyclotron, where they believe positive heavy mesons, decaying into light mesons, are being made, but so far none has been observed, primarily because of the heavy radiation inside the chamber which obscures the elusive tracks of mesons on emulsions. With the development of new methods, the positive mesons are expected to be found. A positive meson would be created from the collision of two neutrons at these high energies.

Dr. Serber cited the following significant implications in connection with meson production:

1. It proves the idea is right that there is an intimate connection between nuclear particles and mesons and between nuclear forces and mesons.

2. With the means now provided to create and observe mesons under controlled conditions in the laboratory, it may be possible to determine what are the ultimate particles of matter, why only these particles exist, and what their properties are. Dr. Serber said, for example, that it is now a simple matter to determine the masses of the mesons, which was of some

uncertainty. The mass can be calculated by the radius of its flight in a magnetic field from target to emulsion and the range of its penetration into the emulsion.

3. The study of mesons will be particularly important in determining the nature of the sub-atomic force which holds nuclei together, a force unlike any other known to man.

4. Techniques will probably be developed, in time, which will enable scientists to study mesons as thoroughly as neutrons and protons. Such techniques would entail the use of specialized Geiger counters.

New "Trigger" For Bomb Suggested

➤ ENERGY MAY BE blasted out of the atom by a lighter weight particle than the prime "trigger" of the atomic bomb, the neutron.

The thoughts of scientists attending a meeting of the American Physical Society in New York turned toward the meson, alias mesotron, the fundamental particle of matter soon after its artificial production. It is generated in nature by powerful cosmic rays entering the earth's outer atmosphere with tremendous energies.

Dr. John A. Wheeler, the young Princeton University physicist specializing on the structure of the atom, has figured out that the most familiar sort of meson (there are probably four or five kinds of them) will produce fission of uranium. It is reasonably probable that it will split asunder the hearts of other heavy atoms with release of energy.

This is a very exciting idea, and one that may be upsetting to the international balance of atomic power. If the meson is aimed at materials that it can fission, it may be necessary to bring other elements than uranium and thorium under control.

Of course, we are a long way from a meson atomic bomb or atomic power plant. The experimental demonstration of meson fission has not yet been made. We are at an earlier stage in the possible realization of meson fission than the world was in 1939 when neutron fission of uranium was demonstrated in Germany.

The least that has happened on this new atomic frontier is that, as Dr. Wheeler says, "experimental and theoretical studies of the interaction of negatively charged mesons with atomic nuclei furnish another point of advance on the elementary particle problem."

What seems to happen is that mesons are able to move in orbits around the atomic nucleus which resemble the orbits of electrons in shape but are in size 200 times smaller. The mesons jump from one of these orbits to another and release energy which should be able to initiate a special type of fission in uranium or heavier nuclei. If they can, the energy release figures out to be about half as much again as the energy given off by uranium that is fissioned by good old reliable neutrons.

Creation of Matter from Energy Will Be Research Goal of Future

The Atomic Nucleus

A New World to Conquer

by Dr. I. I. Rabi

➤ The electrical constitution of matter, that is, the fact that matter is made of constituents which are electrically charged positive and negative, was clearly understood only at the turn of the last century. The fundamental fact of atomic structure, that the atom is made up of a central positive core, the nucleus of the atom, which is positively charged and surrounded by electrons charged negatively, was realized only after 1911 from the great work of Rutherford.

However, it was not until after the work of Bohr, Einstein, Schrodinger, Hisenberg, Pauli, and Dirac, that we had adequate intellectual tools to understand atomic structure. By the end of 1928 the job was complete. The fundamentals had been understood and the structure of the atom was a problem which, in principle, had been solved. The atom had been conquered, but conquest and consolidation are two very different things.

Newton almost three hundred years ago gave the fundamental theory of the solar system and celestial mechanics, yet there are astronomers and mathematicians working on these very problems even today. One hundred years from now there will be physicists, chemists, and engineers working on important problems of atomic and molecular structure.

Long before the fundamental principles of atomic structure had been understood very important advances had been made both in theory and application because practical results do not depend on detailed knowledge of the basic laws.

Our subject today, however, is not the structure of the atom but the atomic nucleus. However, in assessing our present position on this problem and forecasting the future there is much we can learn from the development of our attempts to understand the atom. Let me sketch very briefly the fundamentals of the problem.

If an atom of uranium were magnified a billion times, it would be the size of a basketball, and if its weight were increased correspondingly it would weigh about a ton. If one were to examine it carefully, one would at first sight see nothing at all, but on very close inspection one would find 92 tiny particles, each much smaller than the point of a very fine needle, moving with enormous speed, approximately inside the confines of the basketball. These are the electrons. Altogether these electrons, small as they would appear, would weigh one half pound.

In the center one would discover a speck of dust about 1/1,000 of an inch in diameter. This is the nucleus of the

atom. Its weight or mass would be a ton, less a half pound, of course, for all the electrons put together. If we take, with Einstein, the famous relation $E=MC^2$, that is, energy is proportional to mass, we see that almost 99.99% of the energy of matter is locked up in the nucleus.

The useful energy we have had available up to the present from fuels such as oil, coal, or food has been chemical energy and generally less than one billionth of the total conceivable energy which is locked in the atom and more particularly in the nucleus. These numbers stir the imagination. They are inspiring and frightening, especially if we remember Hiroshima.

Nucleus of the Atom

However, I am not predicting the release of these stupendous powers. We have a long way to go before we can even begin to assess the validity of such speculations. Let us examine further this speck of dust we called the nucleus of the uranium atom.

Looked at more closely it would turn out to be comprised of 238 objects, 92 protons all positively charged and 146 neutrons, 238 in all. I did not pick uranium 235 because that is fissionable material and is classified secret. The protons are all positively charged and have the same charge as the electrons. The neutrons have no charge at all.

We now come to the fundamental question. What forces keep this conglomeration of protons and neutrons together against the mighty repulsions of the protons for one another? What force keeps these nuclear particles which move at tremendous speeds from flying apart in less than one billion billionth of a second? I don't know. Neither does Professor Bethe, even though he knows what makes the sun shine so brightly; nor does anybody else in the whole world.

There are some charming speculations which may contain some grains of truth. I will tell you something about them, but first I must say that our ignorance is not entire. Although the why of nuclear forces is not known, we have a very definite notion about the magnitude of these forces. Otherwise the atomic bomb could not be made and we could not be seriously discussing the use of nuclear energy for the production of power. Application of scientific discovery does not have to wait on complete understanding of the whys and wherefores.

The utilization of atomic energy, whether for warfare or the greater arts of peace and healing, does not await a great basic discovery. The fundamental science is at hand, and it is a question for the engineer, the chemist, the metallurgist, and applied science in general.

We are now concerned with much more fundamental questions which look beyond the immediate practical problems of today but which may bring the headaches of the future. We will now proceed from what may be considered the more or less well-known to what is known only partially and on into the unknown.

At this point the taxpayer, the proverbial hard-headed businessman, or

even the average man about town or Congress may say: Stop! Haven't you made trouble enough? Why not take a recess from your fundamental problems and let us make some order of the mess you have just dropped in our laps? Why not go off and study some politics, economics, sociology, psychology, or even psychoanalysis, and help us solve our vexing problems of human relations and organization? Sufficient unto the day is the evil thereof.

Science is Adventure

One can say a number of things in reply. In the first place, we are far too busy to stop. Science just can't be turned on and off. We, in common with the rest of humanity, are embarked on an adventure from which there is no turning back. We always have to learn more in order to get along with what we have. Who knows what great discovery awaits us tomorrow or the next day? One can hint darkly about our competitors both present and prospective.

One could give the easy, truthful answer that the solution of these problems has almost always paid high dividends in the material welfare of the nation. It has increased production, improved transportation and communication. It has helped combat illness and disease. It has been a powerful weapon in the battle against ignorance and superstition.

This is essentially the answer of the alchemist to his patron. Give me a laboratory and equipment, support me in my experiments, and I will find you the philosopher's stone which will make you richer, healthier, and more powerful. He asked nothing for himself but the love and favor of his noble patron. That the ancient alchemists discovered many important and useful things, there is no doubt. They did not find the philosopher's stone. We, their descendants, have come somewhat closer to the goal and much of the alchemist's attitude survives into the present day.

The extreme of this attitude is to be found in Soviet Russia. There the scientist holds a very high place in society. Although his altitude is high, his permissible horizons are narrow. He is expected to produce discoveries which will not only strengthen the State but which will support the doctrines of the dominant group. For success he receives great rewards, country estates, servants, Lincoln limousines, and well-equipped laboratories. I have heard on good authority that when the atomic bomb exploded over Hiroshima the salaries of Soviet nuclear physicists were trebled. These are mighty great incentives. No prize stallion or highly bred milk cow could have better treatment, but I doubt whether the Soviet scientists find happiness and inspiration in their exalted condition.

From the standpoint of basic science such limited and materialistic motivation is irrelevant and even vulgar. One might as well give a social motivation for artistic creation in that it attracts tourists, or for poetry that it ultimately freshens up the phraseology for advertising slogans.

The real reason for basic research is to expand the boundaries of knowl-

edge pure and simple. It is an expression of the human spirit. This passion for new knowledge, for the exploration of nature is strong in some, easily controllable in others, and in many people completely absent. Various societies have differed in this respect. The Athenians were passionately devoted to the search of abstract knowledge. The Spartans, on the other hand, were quite indifferent.

Fortunately we are living in a time in our country when the interest in scientific research and discovery is mounting very rapidly. All over the country great new laboratories are arising in all fields. Schools of art and music are multiplying. The country is growing up and some of the energy which went into the conquest of this continent is turning toward intellectual and artistic endeavor. We may see the dawn of a Golden Age. Perhaps it has already come and we are no more aware of it than the Athenians in the time of Pericles.

Let us return to the examination of the atomic nucleus just for the sheer pleasure and interest of it. To study an object as small as the atomic nucleus is even more difficult than it sounds. In the first place, you know that one can see smaller objects with the ultraviolet ray microscope than with an ordinary microscope using visible light. The reason is that the wavelength is shorter in the ultraviolet. More recently you have heard of the electron microscope which sees things even smaller, because electron waves can be utilized which are very much shorter. The large synchrotron which is now nearing completion will produce electron wavelengths and gamma rays which are a sort of supershort ultraviolet, of approximately the size of the nucleus. In a certain broad sense the plan is to take a look-see at the atomic nucleus with these extraordinarily powerful instruments.

What will Professor Wilson and his crew of merry men see? If he knew, he would not have built the instrument, but we can conjecture some of the strange things he might see and study. In the first place, the energy of the radiation, although compressed in volume, comes in such enormous packets of about 300 million volts, compared with 3 volts of ordinary light, that mostly chips in the form of protons and neutrons will come out of the nucleus. These chips will interest them enormously but will probably not be the main show.

Particles Created

The chief phenomenon will be in the class which has already been observed in cosmic rays and in the large synchrocyclotron at Berkeley. When these ultra high energy particles strike a nucleus, new particles come out which were not supposed to be there in the first place. They cannot be within the nucleus for reasons which would be too lengthy to give in this lecture. Yet they come out of the nucleus under the extreme condition of high energy impact. The only possibility is that they are created then and there on the instant out of the energy of the collision.

This fascinating phenomenon was first observed by Carl Anderson in Pasadena. When gamma rays of over

a million volts energy strike an atomic nucleus, a pair of electrons comes out once in so often, one positive and one negative. Vice versa, a positive electron and a negative electron can combine leaving nothing but gamma radiation, which is pure light energy.

In the big Berkeley cyclotron it was observed only a short time ago by Lattes and Gardner that when a 400 MEV nucleus of helium struck a carbon nucleus, a new particle appeared, perhaps identical with one previously observed in cosmic rays by Powell and his group in Bristol, England, about a year ago. This new particle has been called a pi meson. It is about 300 times as heavy as an electron and can have either positive or negative charge. The pi meson does not last very long, only about one hundred millionth of a second, and then it turns into two other things. One of these is another kind of meson of about 200 electron mass units. The other partner is at present unknown.

This phenomenon was first observed in cosmic rays by the Bristol group a little earlier, although we have no real assurance that the Berkeley and Bristol phenomena are identical. The mu meson, which may be identical with a particle which Anderson in Pasadena and Street in Harvard found in cosmic rays about 1935, does not linger with us very long either. After about a millionth of a second it turns into an electron and something else which is also unknown.

What do these phenomena mean? It is far too early to tell. No one knows how many more particles will be found in the next few years, after the new machines are in operation, or perhaps in the next few months or days.

Yet, strangely enough, some of these discoveries were foreshadowed in 1935 by the Japanese theoretical physicist Yukawa. He was then about 27 years old. He reasoned from the fact that nuclear forces were short range like the cohesive force of a glue which is very strong on close contact but disappears on a small separation, that the forces could not be electrical in nature, since these are long range forces like gravitational forces.

On the other hand, if one postulated that a proton or neutron in a nucleus could spontaneously emit a massive particle which could be absorbed by another proton or neutron, and vice versa, such short range forces could be explained. Shortly afterward, following this same lead, Anderson and Street independently discovered the mu meson which could be such a particle but isn't. Perhaps the pi meson is this Yukawa particle. It has been suggested with justice that they be called Yukons.

We see that somehow there may be a connection between these new particles and nuclear forces. Why there are so many, why they should disintegrate so quickly and spontaneously, we don't know. We don't know how many there are, or just how they behave in the neighborhood of a nucleus, or anything solid about them really. The young men and women who expect to be physicists will have plenty of problems to study.

Before I close I want to tell you of the most charming new particle of all, the neutrino. This particle has never been observed at all, but, like the God

of the philosopher, if it did not exist it would have to be invented. It comes about in this way. Some nuclei, like rubidium or potassium, spontaneously emit electrons and change into another kind of nucleus. Yet there cannot be any electrons within the nucleus itself. They are just created and come out. On the other hand, they do not all come out with the same energy even though there is a definite energy difference between the energy of the original and final nucleus. This is more than tragedy, because the law of the conservation of energy, without which we would not know how to turn around in physics, says that any energy lost must appear in some other place. That is where the neutrino comes in; it is a particle invented to carry off the missing energy in order to keep the books straight. There is a similar law about spin, and the neutrino takes care of that, too. It is a most convenient little gadget.

After it had been invented, consequences as to its properties could be drawn fairly easily. The most striking property is that it has no mass whatever. It interacts with matter so slightly that it could pass right through the earth in its thickest part without hindrance. For this reason there is no known way of detecting it. It is merely the subject of the verbs "to be" and "to spin."

I hoped in this talk to show you that we physicists don't know everything. That it is not a depressing subject, hopelessly involved in atomic warfare, but a great and exciting, civilized, intellectual adventure. Your new Institute of Nuclear Physics puts you right in the center of this wonderful life, and I wish you joy and great discoveries.

➤ Isidor Isaac Rabi *was born in Austria in 1898, but was brought to America as a baby. After getting his Ph.D. at Columbia University, New York City, he studied in Europe. He then returned to Columbia, where he is now professor of Physics. His specialties are magnetism, quantum mechanics, nuclear physics and molecular beams. The address reprinted here from the Nov. 1948* Chemistry *was delivered at the dedication of the Laboratory of Nuclear Studies at Cornell University.*

Electron Orbits Form Shells Around the Atomic Nucleus

Electron Shells

by HELEN M. DAVIS

➤ THE ATOM, in spite of its minute size, is a highly organized structure. Around the tightly packed nucleus planetary electrons circle in orbits much more complex than those of the planets in our solar system. To be sure, the nine or ten planetary orbits around our sun would correspond to a fairly simple atomic system. Yet in the simple systems around the nucleus of even the lightest elements there is more complexity than astronomers find among our planets.

The structure within the atom appears from chemical evidence to form a series of concentric shells traced out by the orbits of the electrons. Hydrogen, the lightest element, has the simplest structure. Its nucleus is one proton, where most of its mass is concentrated. Its outer structure is one electron, weighing 1/1800 as much. The charge of positive electricity on the nucleus balances the negative charge of the electron revolving around it.

The structure of the hydrogen atom is the inmost structure of each of the other elements. Heavier elements are built up by addition of protons and neutrons to the nucleus, with an added electron in an outer orbit, to balance each proton. Neutrons, which are electrically neutral, add weight to the system without changing its nature. Addition of a proton, however, transmutes the element to the next heavier kind of matter.

Addition of a neutron to the one proton of hydrogen's nucleus makes deuterium, or "heavy hydrogen." The difference modifies some of the physical properties of the element and its compounds. Chemically it is much the same. But, because addition of the neutron increases the atomic weight so much in proportion to that of hydrogen, the difference between the two isotopes of this lightest element is greater than that between isotopes of many of the heavier elements.

Deuterium, with one proton and one neutron, is, chemically, hydrogen. So is tritium, the artificially-formed radioactive isotope whose nucleus holds one proton and two neutrons. A nucleus with one neutron and two protons, on the other hand, is one form of the next heavier element, helium. Another, more usual isotope of helium has two protons and two neutrons in the nucleus.

Helium's chemical properties are practically non-existent, since it is one of the inert elements which form no compounds. This characteristic of the inert elements is believed to accompany a completed "shell" in the outer electron structure of the atom. Wave-mechanics principles also fit the idea that helium's two electrons, spinning in opposite directions, are all that can be held in the position closest to the nucleus.

Because helium has so well balanced a configuration, it is an exceptionally

stable material. When heavy atoms go to pieces, helium nuclei are end products of the radioactive disintegration. Named before they were identified, they are known as alpha particles. Speeded up in "atom smashers," they can in turn be used as atomic projectiles to break up other atoms. Protons, deuterons and tritons, hearts of the three isotopes of hydrogen, can also be used as atomic projectiles. By interaction of these light particles with each other and with heavier elements, much information is being compiled on structure of all the elements.

By combining what is learned from atomic disintegrations, from synthesis of elements heavier than uranium, from the chemical properties of the elements, and from the lines of their spectra, interpreted in the light of quantum mechanics, the structure of the electron shells of each of the elements has been determined.

Chemical properties of an atom depend upon the position of the outer electrons in the atom's shells, and changes of valence are believed to accompany shifts of electrons from one shell to another. Ionization consists of gain or loss of electrons in the outermost orbits. The formation of chemical compounds is accompanied by rearrangements of these structures.

Bright-line spectra in the visible region arise from disturbances of electron structure in the outer shells, while the simpler X-ray spectra come from disturbances in shells closer to the nucleus. The mathematical description of spectrum lines expresses them as the difference between two energy terms. This difference Niels Bohr interpreted as the "jump" of an electron from one orbit to another. It may also be thought of as analogous to a "beat" in music, the perceptible result of interference between two wave-trains. Bohr's great contribution was that he worked out empirically data which, years later, fitted into wave mechanics formulas, when they were worked out.

Electron shells are designated by letters, beginning with K for the shell next to the nucleus. Hydrogen has its one electron in its K shell. Helium has its two electrons in the K shell, and these complete the number that the K shell can hold.

An atom whose electron shells are all complete has no chemical combining power. Helium, atomic number 2, is the first such element. The others are: 10 neon, 18 argon, 36 krypton, 54 xenon, and 86 radon. These are the inert gases of Group Zero in the Periodic Table.

The K electron shell, which can hold no more than two electrons, is the innermost shell of each element heavier than helium. The next, or L shell, begins with lithium, element number three. Lithium's third electron takes its place outside the K shell formation around the nucleus, and this position gives lithium its valence of one when, by ionization, that electron's place is vacant. Beryllium, the fourth element, has two electrons in the L shell. These two electrons complete the first of the two sub-shells which the L shell can hold.

The first sub-shell of each of the electron shells is labelled "s," the next one "p." Boron, the fifth element, begins the "p" sub-shell with its fifth electron. The "p" sub-shell can hold six electrons, and these are filled in in

List of Elements Showing Grouping of Electrons in Shells

Shells		K	L		M			N				O				P				Q
Sub-Groups		1s	2s	2p	3s	3p	3d	4s	4p	4d	4f	5s	5p	5d	5f	6s	6p	6d	6f	7s
1	H	1																		
2	He	2																		
3	Li	2	1																	
4	Be	2	2																	
5	B	2	2	1																
6	C	2	2	2																
7	N	2	2	3																
8	O	2	2	4																
9	F	2	2	5																
10	Ne	2	2	6																
11	Na	2	2	6	1															
12	Mg	2	2	6	2															
13	Al	2	2	6	2	1														
14	Si	2	2	6	2	2														
15	P	2	2	6	2	3														
16	S	2	2	6	2	4														
17	Cl	2	2	6	2	5														
18	A	2	2	6	2	6														
19	K	2	2	6	2	6		1												
20	Ca	2	2	6	2	6		2												
21	Sc	2	2	6	2	6	1	2												
22	Ti	2	2	6	2	6	2	2												
23	V	2	2	6	2	6	3	2												
24	Cr	2	2	6	2	6	5	1												
25	Mn	2	2	6	2	6	5	2												
26	Fe	2	2	6	2	6	6	2												
27	Co	2	2	6	2	6	7	2												
28	Ni	2	2	6	2	6	8	2												
29	Cu	2	2	6	2	6	10	1												
30	Zn	2	2	6	2	6	10	2												
31	Ga	2	2	6	2	6	10	2	1											
32	Ge	2	2	6	2	6	10	2	2											
33	As	2	2	6	2	6	10	2	3											
34	Se	2	2	6	2	6	10	2	4											
35	Br	2	2	6	2	6	10	2	5											
36	Kr	2	2	6	2	6	10	2	6											
37	Rb	2	2	6	2	6	10	2	6			1								
38	Sr	2	2	6	2	6	10	2	6			2								
39	Y	2	2	6	2	6	10	2	6	1		2								
40	Zr	2	2	6	2	6	10	2	6	2		2								
41	Nb	2	2	6	2	6	10	2	6	4		1								
42	Mo	2	2	6	2	6	10	2	6	5		1								
43	Tc	2	2	6	2	6	10	2	6	6		1								
44	Ru	2	2	6	2	6	10	2	6	7		1								
45	Rh	2	2	6	2	6	10	2	6	8		1								
46	Pd	2	2	6	2	6	10	2	6	10		0								
47	Ag	2	2	6	2	6	10	2	6	10		1								

List of Elements Showing Grouping of Electrons in Shells

Shells		K	L		M			N				O				P				Q
Sub-Groups		1s	2s	2p	3s	3p	3d	4s	4p	4d	4f	5s	5p	5d	5f	6s	6p	6d	6f	7s
48	Cd	2	2	6	2	6	10	2	6	10		2								
49	In	2	2	6	2	6	10	2	6	10		2	1							
50	Sn	2	2	6	2	6	10	2	6	10		2	2							
51	Sb	2	2	6	2	6	10	2	6	10		2	3							
52	Te	2	2	6	2	6	10	2	6	10		2	4							
53	I	2	2	6	2	6	10	2	6	10		2	5							
54	Xe	2	2	6	2	6	10	2	6	10		2	6							
55	Cs	2	2	6	2	6	10	2	6	10		2	6			1				
56	Ba	2	2	6	2	6	10	2	6	10		2	6			2				
57	La	2	2	6	2	6	10	2	6	10		2	6	1		2				
58	Ce	2	2	6	2	6	10	2	6	10	2	2	6			2				
59	Pr	2	2	6	2	6	10	2	6	10	3	2	6			2				
60	Nd	2	2	6	2	6	10	2	6	10	4	2	6			2				
61	Pn	2	2	6	2	6	10	2	6	10	5	2	6			2				
62	Sm	2	2	6	2	6	10	2	6	10	6	2	6			2				
63	Eu	2	2	6	2	6	10	2	6	10	7	2	6			2				
64	Gd	2	2	6	2	6	10	2	6	10	7	2	6	1		2				
65	Tb	2	2	6	2	6	10	2	6	10	8	2	6	1		2				
66	Dy	2	2	6	2	6	10	2	6	10	9	2	6	1		2				
67	Ho	2	2	6	2	6	10	2	6	10	10	2	6	1		2				
68	Er	2	2	6	2	6	10	2	6	10	11	2	6	1		2				
69	Tm	2	2	6	2	6	10	2	6	10	12	2	6	1		2				
70	Yb	2	2	6	2	6	10	2	6	10	13	2	6	1		2				
71	Lu	2	2	6	2	6	10	2	6	10	14	2	6	1		2				
72	Hf	2	2	6	2	6	10	2	6	10	14	2	6	2		2				
73	Ta	2	2	6	2	6	10	2	6	10	14	2	6	3		2				
74	W	2	2	6	2	6	10	2	6	10	14	2	6	4		2				
75	Re	2	2	6	2	6	10	2	6	10	14	2	6	5		2				
76	Os	2	2	6	2	6	10	2	6	10	14	2	6	6		2				
77	Ir	2	2	6	2	6	10	2	6	10	14	2	6	7		2				
78	Pt	2	2	6	2	6	10	2	6	10	14	2	6	8		2				
79	Au	2	2	6	2	6	10	2	6	10	14	2	6	10		1				
80	Hg	2	2	6	2	6	10	2	6	10	14	2	6	10		2				
81	Tl	2	2	6	2	6	10	2	6	10	14	2	6	10		2	1			
82	Pb	2	2	6	2	6	10	2	6	10	14	2	6	10		2	2			
83	Bi	2	2	6	2	6	10	2	6	10	14	2	6	10		2	3			
84	Po	2	2	6	2	6	10	2	6	10	14	2	6	10		2	4			
85	At	2	2	6	2	6	10	2	6	10	14	2	6	10		2	5			
86	Rn	2	2	6	2	6	10	2	6	10	14	2	6	10		2	6			
87	Fa	2	2	6	2	6	10	2	6	10	14	2	6	10		2	6			1
88	Ra	2	2	6	2	6	10	2	6	10	14	2	6	10		2	6			2
89	Ac	2	2	6	2	6	10	2	6	10	14	2	6	10		2	6	1		2
90	Th	2	2	6	2	6	10	2	6	10	14	2	6	10	1	2	6	1		2
91	Pa	2	2	6	2	6	10	2	6	10	14	2	6	10	2	2	6	1		2
92	U	2	2	6	2	6	10	2	6	10	14	2	6	10	3	2	6	1		2
93	Np	2	2	6	2	6	10	2	6	10	14	2	6	10	5	2	6			2
94	Pu	2	2	6	2	6	10	2	6	10	14	2	6	10	5	2	6	1		2
95	Am	2	2	6	2	6	10	2	6	10	14	2	6	10	7	2	6			2
96	Cm	2	2	6	2	6	10	2	6	10	14	2	6	10	7	2	6			2

List of Elements Showing Grouping of Electrons in Shells

Shells		K	L		M			N				O				P				Q	
Sub-Groups		1s	2s	2p	3s	3p	3d	4s	4p	4d	4f	5s	5p	5d	5f	6s	6p	6d	6f	7s	7p
97	Bk	2	2	6	2	6	10	2	6	10	14	2	6	10	8	2	6	1		2	
98	Cf	2	2	6	2	6	10	2	6	10	14	2	6	10	9	2	6	1		2	
99		2	2	6	2	6	10	2	6	10	14	2	6	10	10	2	6	1		2	
100		2	2	6	2	6	10	2	6	10	14	2	6	10	11	2	6	1		2	
101		2	2	6	2	6	10	2	6	10	14	2	6	10	12	2	6	1		2	
102		2	2	6	2	6	10	2	6	10	14	2	6	10	13	2	6	1		2	
103		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	1		2	
104		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	2		2	
105		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	3		2	
106		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	4		2	
107		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	5		2	
108		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	6		2	
109		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	7		2	
110		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	8		2	
111		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	9		2	
112		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	10		2	
113		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	10		2	1
114		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	10		2	2
115		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	10		2	3
116		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	10		2	4
117		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	10		2	5
118		2	2	6	2	6	10	2	6	10	14	2	6	10	14	2	6	10		2	6

the following elements: 6 carbon, 7 nitrogen, 8 oxygen, 9 fluorine and 10 neon. Neon has a complete L shell, and consequently the properties of an inert gas.

While chemists refer to the complete electron shells by letter, the K shell, the L shell, the M shell, and so on, this nomenclature becomes clumsy when the distinction between their sub-shells is to be discussed. For this purpose the number of the large shell outward from the nucleus is used. The K shell is thus 1s, the subgroups of the L shell are 2s and 2p, while the three subgroups of the M shell are 3s, 3p and 3d. With the N shell, a fourth subgroup appears, so that the subgroups of N are 4s, 4p, 4d and 4f.

The letters designating the subgroups came from an older attempt to classify the lines of the spectrum. They stand for *sharp, principal, diffuse,* and *fundamental*. These descriptions do not fit the character of the lines very accurately, but the types of lines to which they refer recur periodically as the electron structure of the elements builds up. The elements with K shell only have spectral lines of the *s* series. In the two subshells of the L shell, the electrons of the inner one emit *s*-type radiation and those of the outer emit the *p*-type.

The M electron shell begins with the element sodium. The single electron in its outside shell gives that element its strong positive valence of one. In the following elements, the M shell continues the development of subshells by completing a two-electron *s* sumshell, a six-electron *p* subshell and

a ten-electron subshell, whose series of spectrum lines is known as *d* (diffuse).

The M shell, however, does not end with production of argon, the next inert gas. This element is reached with the completion of sub-shell *p* in the M shell. But, after argon, a rearrangement of electrons takes place and the outer *d* sub-shell remains vacant in the next two elements, potassium and calcium, while a new N shell begins to form its first *s* layer. The accompanying table shows the structure of the shells for each of the known elements, and the probable structure of the hypothetical elements expected to complete the known pattern of the Periodic Table.

Our information on electron shells is derived from measurement of spectrum lines, interpreted by the principles of wave mechanics. The data can be checked by a number of independent measurements. The determining factor in whether an electron enters one or another of the shells available is the energy requirement. In some cases the energy levels of two states within the atom are almost the same, and an electron is almost as likely to enter one of the subgroups as the other.

Of great interest in connection with electron shells are the lanthanide series of elements, in which the 4f shell is filling, which extends from element 57 lanthanum or the following 58 cerium through 71 lutecium, and the actinide series, in which the 5f shell is filling, which extends similarly from element 89 actinium or 90 thorium through hypothetical element 103. It was not until the transuranium elements had been made and their properties studied that the true nature of this second group of "rare earth" elements was understood and uranium properly placed in the Periodic Table. Niels Bohr had, however, predicted such a group on theoretical grounds.

The structures of the O shell (5s, 5p, 5d, 5f) and the P shell (6s, 6p, 6d, 6f) seem to follow that of the N shell although, as is evident from the accompanying table, the list of elements is theoretically far from complete and the heaviest elements, including the six man-made ones, have not yet filled more than the 7s sub-shell of Q.

Atomic Number and Nuclear Structure

➤ THE NUMBER of positive charges in the nucleus is called the atomic number, Z. It determines the number of electrons in the extranuclear structure, and this in turn determines the chemical properties of the atom. Thus all the atoms of a given chemical element have the same atomic number, and conversely all atoms having the same atomic number are atoms of the same element regardless of possible differences in their nuclear structure.

The nuclei of all atomic species are made up of neutrons and protons. The number of protons is equal to the atomic number Z. The number of neutrons, N, is equal to the difference between the mass number and the atomic number, or $A - Z$.

—Smyth Report

Measurements in Nuclear Physics Are Expressed in These Units

Units of Mass, Charge and Energy

➤ MEASUREMENTS *in the newer physics basic to atomic power are in terms of the units defined here. Both the definitions and the useful conversion table are from the Smyth Report, authorized standard text on things atomic.*

Mass

Since the proton and the neutron are the fundamental particles out of which all nuclei are built, it would seem natural to use the mass of one or the other of them as a unit of mass. The choice would probably be the proton, which is the nucleus of a hydrogen atom. There are good reasons, historical and otherwise, why neither the proton nor the neutron was chosen. Instead, the mass unit used in atomic and nuclear physics is one-sixteenth of the mass of the predominant oxygen isotope, O^{16}, and is equal to 1.6603×10^{-24} gram. Expressed in terms of this unit, the mass of the protons is 1.00758 and the mass of the neutron is 1.00893. (Chemists usually use a very slightly different unit of mass.)

Charge

The unit of electric charge used in nuclear science is the positive charge of the proton. It is equal in magnitude but opposite in sign to the charge on the electron and is therefore often called the electronic charge. One electronic charge is 1.60×10^{-19} coulomb. It may be recalled that a current of one ampere flowing for one second conveys a charge of one coulomb; *i.e.*, one electronic charge equals 1.60×10^{-19} ampere second.

Energy

The energy unit used in nuclear physics is the electron volt, which is defined as equal to the kinetic energy which a particle carrying one electronic charge acquires in falling freely through a potential drop of one volt. It is often convenient to use the million-times greater unit: million electron volt (Mev). A billion electron volts is Bev.

The relationships among the electron volt and other common units of energy are in the following table:

Conversion Table for Energy Units

Multiply	*By*	*To Obtain*
Mev	1.07×10^{-3}	mass units
	1.60×10^{-6}	ergs
	3.83×10^{-14}	g. cal.
	4.45×10^{-20}	kw. hrs.
mass units	9.31×10^{2}	Mev
	1.49×10^{-3}	ergs
	3.56×10^{-11}	g. cal.
	4.15×10^{-17}	kw. hrs.
ergs	6.71×10^{2}	mass units
	6.24×10^{5}	Mev
	2.39×10^{-8}	g. cal.
	2.78×10^{-14}	kw. hrs.
g. cal.	2.81×10^{10}	mass units
	2.62×10^{13}	Mev
	4.18×10^{7}	ergs
	1.16×10^{-6}	kw. hrs.
kw. hrs.	2.41×10^{16}	mass units
	2.25×10^{19}	Mev
	3.60×10^{13}	ergs
	8.60×10^{5}	g. cal.

Conditions Met on Earth Unusual in the Universe

Atomic Energy Common, Fire Rare

by William G. Pollard

➤ First I want to say something about what atomic energy is. Perhaps the best way to do this is to compare it with the more familiar chemical energy. Chemical energy is the kind of energy released when coal, wood, or gasoline is burned or when TNT explodes.

We get chemical energy because things called atoms exert forces on each other and get drawn together by these forces into groups called molecules. In chemistry the different kinds of atoms are called elements. Some of the elements are hydrogen, helium, lithium, beryllium, boron, carbon, nitrogen, and oxygen, to name them in order of increasing weight. Air is made up primarily of oxygen and nitrogen. But not in the form of atoms. Two oxygen atoms attract each other and pull together to form a molecule of oxygen in the form of a dumbbell. Nitrogen and hydrogen atoms do the same thing. They form groups of two held together fairly strongly.

Coal is made up of carbon atoms. Let us see what happens when coal burns. A carbon atom, when it comes close to two oxygen atoms held together as an oxygen molecule, is strongly attracted to the mid-point between them. The strong force pulling it into place causes both to move rapidly toward each other. They vibrate very rapidly as a result and this excessive motion is transferred to other molecules which strike the group. All this excessive motion appears to you as great heat. This is what burning coal consists of. The oxygen molecules attract carbon atoms as a magnet attracts a nail. Under this force, the particles are speeded up, vibrate rapidly, and transfer this excess motion to other atoms and molecules. When these others move rapidly we say they are hot. We say the coal is burning. The result of this burning is to fasten the carbon atom and the oxygen molecule into a group of three atoms called a molecule of carbon dioxide.

At the center of every atom is what we call the nucleus of the atom. It is about 100,000 times smaller than the atom and contains most of the weight of the atom like the solar system and the sun. Back in 1930 we found that the nucleus was made up of smaller particles called neutrons and protons. These are held together by strong forces in groups of several neutrons and protons and such groups form the nuclei or cores of all atoms. Now just as chemical energy comes from some groups of atoms pulling together to form new groups, atomic energy comes from some groups of neutrons and protons pulling together to form new groups. Nuclear physics is therefore very much like chemistry. In one we have certain elements called atoms which pull together into groups

called molecules. In the other we also have elements, but there are only two of them called neutrons and protons. These two pull together to form groups. These groups we call atomic nuclei or isotopes instead of the corresponding word molecules in chemistry. We have different isotopes of the same chemical element by having groups with different numbers of neutrons and the same number of protons.

The one big difference between chemical and nuclear reactions is the amount of energy involved. The forces holding neutrons and protons together are enormously greater than those holding atoms together in molecules. When two or more nuclear particles are pulled together to form a new nucleus or isotope, the speeds which these forces impart to them are beyond anything in our experience. In general they are about a million times greater than the speeds acquired when atoms go together to form molecules.

To pull a bar of steel apart you have to overcome the forces which iron atoms exert on each other in holding it together. In terms of the corresponding force you would have to exert to pull the nucleus of an atom apart, split it, say, these nuclei of atoms are several million times stronger than steel.

We can look at it this way: When coal is burned, the speeding up of the atoms corresponds to heat energy of about 4 kilowatt hours per pound of coal burned. Burning fifty pounds of coal releases 200 kilowatt hours, or about the electric bill of an ordinary household for a month. Now the nuclei of the atoms of the metal lithium at very high temperatures and pressures will unite with hydrogen atoms or protons to form two nuclei or atoms of helium. This is a nuclear reaction. The two helium atoms fly apart with enormous speeds under the forces acting on the nuclei. The speed is so great that the resulting heat energy is 30,000,000 kilowatt hours per pound of lithium burned, enough to run our ordinary residence twelve and a half thousand years!

The burning of one ton of coal will keep the power plant at the University of Tennessee running for about two hours. If there were any practical way to burn lithium with hydrogen, (there is none, as we shall see shortly), one pound would keep it going for a year. There is, however, a kind of nuclear furnace called a "pile" which burns uranium with neutrons, instead of lithium with protons, which is in operation now at Oak Ridge. This plant produces just about the same amount of heat all the time as our University power plant does. It is roughly the same size building as our power plant and they both have roughly the same output. It has been operating pretty nearly continuously for almost three years now and during that time it has consumed around five pounds of fuel. Compare this with the amount of coal consumed in the University power plant in the same time!

There are three points I wish to make now. The first concerns the impression that atomic or nuclear energy is a very rare thing only just now discovered and that chemical energy as in burning wood or coal is very common. It is, in fact, just the re-

verse. There are many nuclear reactions in addition to joining lithium and hydrogen which can give these enormous quantities of energy. They are extremely common in the universe. They are going on today in most of the matter in the universe. All of the heat poured out of the sun and all other stars comes from these reactions. In most of them hydrogen is being burned to form helium. Ordinary fire, on the other hand, is almost certainly extremely rare. It requires an atmosphere containing free oxygen and supplies of free carbon that can only come from living matter. So far as we know, our own earth is the only place in the whole universe where it can occur.

Why, then, if the nuclear reaction is so common, have men not produced it before? To start an ordinary fire you have first to ignite it, that is, produce a high temperature in one spot. A nuclear fire requires the same thing except you have to produce a temperature of several million degrees. In the sun the reaction is just barely ignited and the temperature is 35,000,000 degrees Fahrenheit. All nuclear reactions with naturally existing materials will burn only at temperatures like this. They also require pressures of many millions of pounds per square inch. You may be sure that we will never use this kind in anything but bombs. Our sun is really an atomic bomb in process of continual explosion.

How, then, can we have atomic power plants? There are quite a number of things like lithium, boron, nitrogen, uranium, and plutonium that can be burned or reacted with neutrons. They give about the same amounts of energy as the nuclear reactions with naturally existing materials not using neutrons. But they do not need high temperatures at all to ignite them. They burn at any temperature as soon as the neutrons are supplied.

The trouble is that there is no natural source of neutrons except in one special case. The nuclei of the heaviest elements are right on the verge of blowing up because of the repulsive forces pushing apart the large number of protons in them. A slight disturbance upsets the balance and the nucleus splits in two. This is called fission. When it happens several neutrons are set free. From a knowledge of the way neutrons are held in all nuclei we can say with assurance that the only way we can make neutrons reproduce themselves and so get great quantities of them is this kind of process.

This brings me to my second point. Most of the heavy atoms such as thorium, protactinium, and uranium can be split with relatively small disturbances but only a few will do so under the particular disturbance caused by capturing a neutron. In fact, only one existing in nature will do so and this is a kind of uranium consisting of 92 protons and 143 neutrons bound together so as to have 235 particles in it. It is an isotope of uranium which we call uranium 235. The common form has 238 particles in it. This makes uranium the key to all applications of atomic power. Other materials, like plutonium, which are just as good as U-235 can be made from U-238, and from thorium, but you have to have lots of neutrons to

do it and these can only be had from uranium.

It is difficult to appreciate the force of these arguments without a background in nuclear physics but they are really foolproof. Many new and remarkable things will be done with atomic energy which we do not foresee at all now. But this we know, that they must all of them start with a heavy element and very probably this element must be uranium. It will be the key to everything. This is the one very fortunate circumstance in the whole disturbing problem of the atomic bomb.

There is a further point of importance. The kind of reaction used in a bomb needs nearly pure U-235 or plutonium or other fissionable isotope. That used in a pile such as the plant at Oak Ridge I told you about is very similar and uses the same fissionable isotopes but they do not have to be pure. They can even be at fairly low concentrations. This means that after making fissionable isotopes other non-fissionable isotopes of the same chemical form can be added. They are then no good for bombs but still good for atomic power plants. So you can denature bomb material, making it useless for bombs but still good for peacetime uses.

These two circumstances—that uranium is the key and that denaturing is possible without harming peacetime applications—form the technical basis of the possibility for controlling atomic energy.

➤ William Grosvenor Pollard *was born in Batavia, N. Y., in 1911. After taking his Ph.D. at Rice Institute, Houston, Tex., and teaching there for a few years, he went as assistant professor to the University of Tennessee. He became executive director of the Oak Ridge Institute of Nuclear Studies in 1947. He works with cosmic rays, beta ray spectra and theory of neutron diffraction by crystals. This address, given as part of a forum on atomic energy before the Tennessee Academy of Science meeting at Vanderbilt University, is reprinted from* Chemistry, *Jan. 1947.*

Atomic Energy Commission Report on Isotopes and Power

Atomic Energy Progress

▶ THIS PAPER proposes to discuss considerations that will determine the answers to the questions:

When shall we have heat and power from atomic energy?

On what scale will this be available?

How much will it cost?

Even if a full account of the events of the next decades were available to us, we would have to give a fairly complex answer to these questions. Thus, the first instances of the generation and uses of heat or power are likely to be on a small scale and be uneconomical. Further development may increase the scale without substantially improving the economy, and many steps surely lie between the present and the ultimate future in which atomic power is possible, economical, practical, and abundant.

At present, there already exist nuclear reactors which produce atomic power as a byproduct but not in a usable form. The large reactors at Hanford, made up of natural uranium and graphite and used in the production of plutonium for atomic bombs, generate great quantities of heat at low temperatures, and this heat is carried away in the water of the Columbia River. The much smaller uranium-graphite reactor at the Oak Ridge National Laboratory, used for research purposes and for the production of radioactive isotopes, generates heat which is dissipated in the air. The reactor at the Brookhaven National Laboratory is similar. The uranium-graphite and the uranium-heavy-water reactors at the Argonne National Laboratory are used for research purposes and their small energy outputs are also wasted. The reactors at the Los Alamos Laboratory, made up of enriched uranium or plutonium and used for research in connection with atomic bombs, operate at a very low power and dissipate their heat into water or into the air. Thus, none of the reactors now in existence produce usable power. However, all of these reactors supply valuable information for the development of power reactors.

There are numerous scientific and technical problems that must be solved before atomic power can become a practical reality. Some of these are connected with generating energy at high temperatures, for no other sound method of applying atomic energy usefully as energy has as yet been proposed. This problem of high-temperature energy generation is essentially one of finding suitable materials for use in a nuclear reactor, suitable forms for the fuel, for structural elements, for coolants, and for moderators. But even in a program focused primarily on high-temperature energy, novel considerations limit the kinds of material which can be used. Thus, any reactor must include

one of the two fissionable elements, uranium and plutonium. Materials of the reactor must be able to withstand not only high temperature, but the high levels of radiation which are necessarily present if the power is not to be altogether trivial.

Neutron Absorbers

To these obvious and necessary requirements, further desirable but optional criteria must be added. For example, it is undesirable to use in a reactor materials which absorb many neutrons, since the investment in nuclear fuel would thereby be increased and its conservation impaired. It is undesirable to use materials or reactor designs which give a very short life without recharging, since this not only works against economy because of the cost and inevitable losses in reprocessing reactor components and fuels, but also limits the adaptability of the source of power. It is undesirable to build reactors in which the power per unit of fuel invested is very low, since this will clearly involve rather large capital fuel costs. It is desirable that the reactor design have as little net consumption of fuel per unit of power as possible, or even that it have a net gain of fuel, a so-called breeding, as power is generated. All of these considerations bear on increasing the possible scale and decreasing the probable cost of atomic power.

However, it is likely that in many early reactor designs these criteria will not be adequately satisfied. These reactors will involve relatively large charges of fuel, relatively low power per unit of fuel invested, frequent recycling, and a high net consumption of fuel per kilowatt obtained. They will also probably operate at moderate temperatures where the thermodynamic efficiency is low and where certain specialized applications may not be possible.

The widespread use of atomic power will also depend on the availability of nuclear fuels. There are three possible nuclear fuels—Uranium 235, Uranium 233, and Plutonium 239. Uranium 235 occurs to the extent of only 0.7 per cent in natural uranium and can be used either in that highly dilute form, or after preliminary enrichment in isotope-separation plants. It is the natural source of all nuclear fuels. Plutonium and Uranium 233 are artificial nuclear fuels obtained in the first instance by absorbing some of the extra neutrons from the fission of Uranium 235 in either Uranium 238 (the inert part of natural uranium) or in thorium. These elements, once formed, can be separated by chemical means from their parents, a simpler process than the physical separation of isotopes but fraught with great difficulties because of the enormously high radiation levels.

Fuel Availability

The selection between the various types of fuel will be, in the long run, a matter of economics and availability. If uranium ores should be found to be very plentiful even if low grade, it would probably be cheapest and best to use natural or, if needed, slightly enriched uranium as a fuel directly. The fuel might then be discarded without chemical treatment

after, say, one per cent had been utilized, which would give about 100,000 kilowatt-hours of heat per pound of the original material.

In anticipation of a rapidly growing shortage of uranium, great attention has been given to "breeding," a process in which plutonium or Uranium 233, is produced by the power reactor at a rate greater than its consumption. It is theoretically possible—but in practice will be very difficult—to build an industrial reactor that will cause excess neutrons to be absorbed in a blanket of either U 238 or thorium, producing plutonium or U 233 which can serve as new fuel to continue the operation indefinitely as long as new natural uranium or thorium is supplied. This greatly increases the availability of fuel, for most of the uranium, not just the small U 235 fraction of it, is consumable, and moreover the larger resources of thorium also can be used. It might even be possible by these means to build up fissionable material faster than it is consumed.

Engineering Difficulties

Nevertheless, the engineering difficulties associated with breeding are enormous. The conditions which have to be fulfilled to obtain high neutron economy are difficult to reconcile with those needed to obtain a high power output for a given material investment. There are acute chemical engineering problems associated with the repeated treatment of partly depleted fuel and the extraction of new fissionable material from the uranium or thorium blanket. Such procedures are complicated by the enormous radioactivity and have to be repeated many times before the fuel is completely consumed. The process must give virtually complete recovery at each stage if the physical reproduction is to be reflected in active material stocks.

Cost of Uranium

Another very important factor in the possibility of widespread use of atomic power will be the cost of uranium. At the price of uranium compounds before the war, the cost of uranium fuel would compete with coal under almost any condition. However, the available supply came from fairly rich ores and was fairly limited. It may be assumed that the supply could be increased through intensive geological research and prospecting. Large use of uranium, however, will certainly drive the mining industry to the exploitation of poorer and poorer deposits. The cost will be determined by the cost of handling large amounts of rock, although it may conceivably be reduced by the sale of useful byproduct minerals.

If unfavorable assumptions are made about the cost of uranium and the technical practicability of breeding, the result is that atomic power would not compete with coal power in the United States except in regions where the cost of transportation of the fuel from the mines is the determining factor, or under other special conditions where the small bulk and weight of the uranium fuel are particularly valuable. On the other hand, if favorable assumptions are made about the cost of uranium and

the technical practicability of breeding, the ultimate capacity may become comparable to or even larger than, the present coal industry and will operate at a lower cost, at least as far as fuel expenditure is concerned. At the present time, sufficient knowledge does not exist to make a definite choice between these two alternative possibilities. It should be pointed out that, in either case, the cost of a nuclear-fuel power plant will be substantially greater than that of a coal-burning plant of similar capacity.

Even on the assumption of a most favorable and rapid technical development along these lines, a word of caution is needed as to the time scale. We do not see how it would be possible under the most favorable circumstances to have any considerable portion of the present power supply of the world replaced by nuclear fuel before the expiration of 20 years.

There has been extensive discussion and speculation on the possibilities of atomic power and in some instances unwarranted optimism as to the character of the technical difficulties and the time required to surmount these difficulties. The above is a 1948 report to the Atomic Energy Commission by its General Advisory Committee[5] stating the Committee's evaluation of the prospects for useful power from nuclear energy.

[5]Members of the AEC General Advisory Committee: Dr. J. Robert Oppenheimer, Director of the Institute for Advanced Study, Princeton, N.J., chairman; Dr. James B. Conant, President of Harvard University; Dr. Lee A. DuBridge, President of California Institute of Technology; Dr. Enrico Fermi, Professor of Physics at the Institute for Nuclear Studies, University of Chicago; Dr. I. I. Rabi, Chairman of the Department of Physics, Columbia University; Hartley Rowe, Vice President and Chief Engineer of the United Fruit Company; Dr. Glenn T. Seaborg, Professor of Chemistry at the University of California; Dr. Cyril S. Smith, Director of the Institute for the Study of Metals, University of Chicago; Hood Worthington, E. I. duPont de Nemours & Co.

Waves and Probabilities

➤ A material particle will have a matter wave corresponding to it, just as a light quantum has a light wave. . . . A wave of matter is equivalent to the probability of finding the particle. According to this view, the whole course of events is determined by the laws of probability; to a state in space there corresponds a definite probability, which is given by the de Broglie wave associated with the state. A mechanical process is therefore accompanied by a wave process, the guiding wave, described by Schrödinger's equation, the significance of which is that it gives the probability of a definite course of the mechanical process. If, for example, the amplitude of the guiding wave is zero at a certain point in space, this means that the probability of finding the electron at this point is vanishingly small.

—*Born: Atomic Physics*

Physicists Teach Engineers Tricks of Nuclear Energy

Atomic Power Engineering

by ALFRED O. NIER

➤ BEFORE ANY GREAT scientific discovery can be put to every day use, there are formidable engineering problems which must be overcome. Although the fundamental principle of the electric generator was discovered in 1831, over half a century passed before electricity found wide-spread use. New and better ways had to be found for making and insulating copper wire. Magnetic materials had to be studied and special steels developed to make practical the present highly efficient generator and motor. The electric light bulb had to be invented and perfected. The steam turbine had to be developed. These and countless other problems had to be solved by engineers and scientists working together in order to bring the electrical industry to where it is today.

Before atomic energy can be used for practical power production, there are many bridges which must yet be crossed. Because of the complexity of the problems, close co-operation between the scientist and engineer will be required in order that each will understand the other's difficulties.

Although the pressure exerted by the steam in a steam engine is produced by the impact of countless molecules on the retaining walls, power engineers have never had to concern themselves much with the nature of collisions between gas molecules, the velocities of molecules, or other details of molecular phenomena studied in detail by physicists and physical chemists. An empirical knowledge of the gross properties of matter has usually been sufficient.

In the atomic engine, as in the steam engine, billions and billions of atoms are involved in the production of useful amounts of work. However, unlike the steam engine where all the atoms of the working substance are undergoing the same processes, the atomic engine has many different processes taking place within it simultaneously, some of which compete with one another for atoms. Thus to understand the performance of an atomic engine we must have a rather detailed knowledge of the behavior of individual atoms.

Let us consider first of all the essential parts of an atomic energy engine of the general sort that has been proposed. In Figure 1 is shown a schematic drawing of such an engine. We see here the pieces of uranium or other fissionable substance surrounded by suitable retaining jackets. In addition to the fissionable substance there must be a moderator, a substance which will slow down the fast neutrons produced in the fission process so that they will be useful in producing more fissions. In operation a neutron strikes a uranium 235 nucleus, blows it apart into two heavy fragments, each having about half the mass of the original atom; loose neutrons are also produced in the process. If the device is properly constructed, many of the neu-

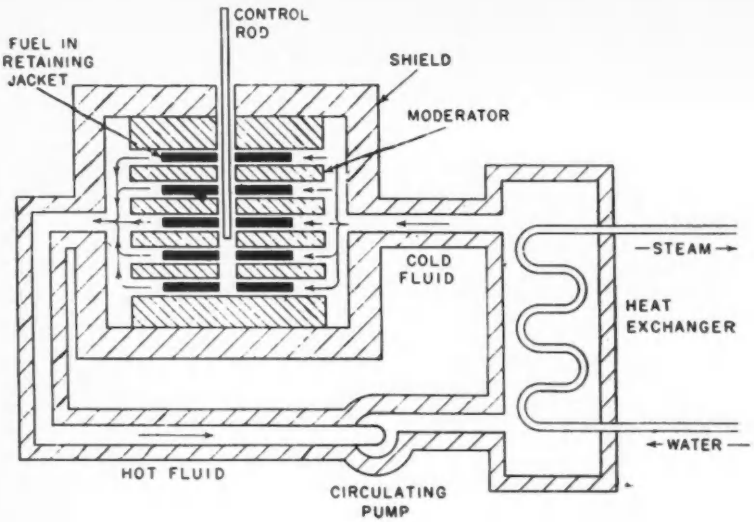


Fig. 1

trons produced will in turn strike other uranium atoms, blow them apart, and produce more neutrons and more energetic atom fragments. In other words, if conditions are properly arranged, we will have a chain reaction; the device will itself furnish the neutrons needed to keep the reaction going and in the process act as a source of energy through the conversion of stored atomic energy into kinetic energy of the fragments formed in the fission process. The kinetic energy is converted into heat which may be removed for utilization by circulating a suitable fluid around the slugs of fissionable material. By means of a heat exchanger, steam can then be produced for operation of conventional power units.

Let us see what some of the requirements of our materials of construction are. First of all, we note that the cans housing the fissionable materials must not absorb too many neutrons. The same may be said of the cooling fluid and the moderator. On the other hand, the rods for controlling the neutron density should be good absorbers as should the shield surrounding the reactor and heat exchanger. The fuel itself must not absorb too many neutrons in non-profitable processes and must contain sufficient active material so that as the fission products build up and cause a parasitic loss of neutrons there will be a sufficient excess production to make up for this loss.

Thus we see that the atomic power engineer must not only concern himself with the ordinary properties of his building materials such as thermal conductivity and expansion, entropy, resistance to corrosion and many others, but he must also be concerned

with the nuclear properties of the materials. Is there any convenient way in which the nuclear properties may be expressed? Yes, there is, if we note that all the effects in an atomic energy generation system are caused by the collisions of particles or rays with materials. This suggests that we describe the nuclear properties in terms of collision probabilities or in terms of a quantity which we call the cross-section of an atom. These are terms which are perhaps new to the engineer, but well known to the physicist.

If you are out duck hunting and a flock of birds passes over your head, your chance of hitting one will depend directly upon the size of a bird or more accurately, upon the cross-sectional area which a bird has when viewed from your position. Your chance of bringing down a mallard would be much better than hitting a canary and if ducks were as large as elephants, your chance of hitting one would be materially improved. Moreover, if you could employ basketballs rather than buckshot, you would stand a still better chance of making hits. In other words, the chance of a collision between a shot and a duck is proportional to the size of the duck and of the projectile used; and so it is with atomic nuclei.

If we send a beam of atomic particles against a block of material, some will make collisions with the atoms in the block, others will pass through as shown in Figure 2. Here we show 16 particles striking the front of the block. In the first element of thickness one-half or eight have made collisions, the remainder passing on into the next element where one-half or four of these make collisions leaving two to

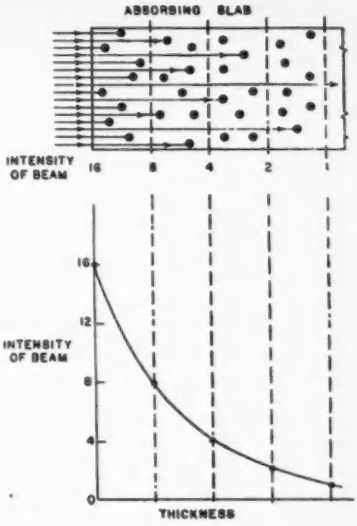


Fig. 2

pass into the next element with only one emerging from the block without having suffered a collision. Had the cross sections of the circles (atoms) been larger, none would have passed through the slab without collision; had the cross sections been smaller, more would have emerged without collision. The cross section is thus a measure of the likelihood of a collision taking place. A large cross section corresponding to a high probability and vice versa.

Now the term "cross section" is useful in describing a whole host of phenomena. For example, we state that Uranium 235 has a certain fission cross section. By this we refer, of course, to the probability that when a beam of neutrons is sent through a thin slab of

material, that a collision will be made which results in fission. Or, we may refer to the elastic collision cross section of an atom in which we refer to the probability of collision taking place without any loss of energy as in the case of the collision of two perfect billiard balls. These are but two examples of the kinds of cross sections atomic physicists talk about. As we shall see, there are others which are useful to define.

Of what order of magnitude are atomic cross sections? In most cases atomic nuclei behave as if they had diameters of about 10^{-12} cm or cross sectional areas of 10^{-24} cm^2. This number varies greatly from element to element and from process to process and for that matter with the speed and nature of the projectiles employed. Thus a statement of the value of the cross section has no meaning unless the exact process involved is also defined. Cross sections greater than 10^{-24} cm^2 are generally considered large. Thus we see some workers measuring cross sections in terms of "barns," the barn representing an area of 10^{-24} cm^2, and the implication being that anything as large or larger than this is "big as a barn."

What are some of the atomic cross sections with which we should concern ourselves in atomic power units? First of all, we should be interested in the fission cross section of our fissionable material. In what follows I will assume that we are using U-235. However, similar arguments will apply to other fissionable substances such as Plutonium 239 and Uranium 233. When a U-235 nucleus undergoes fission, the neutrons released have a rather high energy. The fission cross section of U-235 is relatively small for high energy neutrons, but large for really slow neutrons in the thermal energy range. Thus if we wish to produce a chain reaction it is to our advantage to slow down the neutrons. Neutrons may be slowed down by making elastic collisions with atomic nuclei. Thus our reactor should contain some substances with which the neutrons may collide. However, in making the collisions we must make sure that the neutrons are not lost in some absorption process. In other words, our slowing down medium, technically called the "moderator," should have a high cross section for elastic collisions and a low cross section for capturing neutrons. In any event, we should try to slow down the neutrons in as few collisions as possible since then there will be a minimum chance of losing neutrons. By the ordinary laws of mechanics, we can show that if we slow down an object, by letting it make an elastic collision with some stationary object, we lose the greatest amount of energy in a collision if the masses of the two objects are equal, in which case, we will lose 50 per cent of the energy per collision. This suggests immediately that we should employ hydrogen as a moderator since the mass of the hydrogen atom is the same as that of the neutron. Thus if we wished to slow down a million electron volt neutron to an energy of 0.1 electron volt, about 20 collisions would be required, (the electron volt is a unit of energy and represents the amount of energy acquired by an electron which falls through a difference of potential of 1 volt). On the other hand, if we chose to lose this energy by allowing collisions with, let

Measurements of Light Elements as Neutron Absorbers

	f	σ_s	$f\sigma_s$	σ_a	$f\sigma_s/\sigma_a$
Hydrogen	0.5	20	10	0.3	30
Helium	0.3	1.5	0.48	0	large
Lithium	0.25	6	1.5	60	0.02
Beryllium	0.22	6	1.3	0.007	185
Boron	0.16	6	.96	700	0.001
Carbon	0.14	5	.7	0.004	175

Fig. 3

us say, carbon atoms which are twelve times as heavy as neutrons, we would lose only 14 per cent of the energy in a collision and we would need 123, or six times as many collisions. However, this is not the entire story for we must also consider the fact that there is a certain probability of absorption of neutrons in our slowing down material. As a matter of fact there are a number of elements for which the absorption cross section is much less than for hydrogen and hence are better moderators in spite of their greater mass. In an article which appeared in the February, 1947 issue of *Instruments*, Dr. E. C. Creutz summarizes this matter very well in a table which I will show as Figure 3. The first column shows the fraction of energy lost by a neutron each time it makes an elastic collision with a nucleus of one of the elements listed. In the second column is shown a rough value for the scattering cross section. The product $f\sigma_s$ is thus a measure of the ease of slowing down a neutron by means of elastic collisions. In column four are shown rough values for the absorption cross section. The larger this quantity is the greater will be the chance of losing a neutron by absorption. Thus the ratio $f\sigma_s/\sigma_a$ can be considered as a figure of merit of the element as a slowing down medium. We see, for example, that helium would be an excellent material to use, but since it is a gas, it would be hard to obtain a high density of atoms without the use of very high pressures. Ordinary hydrogen is not especially good. Heavy hydrogen, not listed, is much better. Lithium and boron, because they absorb neutrons so readily, are very poor substances to use as slowing-down media. On the other hand, beryllium and carbon are very good. Because of the availability of the latter in the form of graphite it was actually used in the chain reacting piles now operating.

Figure 3 is useful in other ways. It shows the need for extremely pure materials of construction. For example, if carbon is used as a moderator, and if it contains only ten parts per million of boron as an impurity as many neutrons will be absorbed by the boron as by the carbon itself.

The competition between profitable and non-profitable utilization of neutrons is one which we must contend with throughout this problem. For example, when ordinary uranium is used as a fuel in a reactor we have 139 times as many U-238 as U-235 atoms present. Now if we plot the absorption cross section of U-238 as a function of neutron energy we find that it has a sharp maximum, or resonance, value at a neutron energy intermediate

between that of the neutrons produced and the energy required for maximum fission of U-235. Thus, in slowing down the neutrons, we stand a good chance in losing a large share of them as they pass through the resonance region. Fortunately, the effect may be minimized by proper geometrical arrangement of the uranium relative to the moderator. In the future, the utilization of uranium in which the U-235 has been enriched will further reduce the importance of this factor.

We have just mentioned that the resonance absorption by U-238 diverted neutrons from accomplishing our main objective, the fission of U-235. However, when we consider what happens as a result of the absorption process we see that this is not a total loss. We find that when a neutron is captured by U-238 the following nuclear reactions take place.

$$_{92}U^{238} + {}_0n^1 \longrightarrow {}_{92}U^{239} \longrightarrow {}_{93}Np^{239} + {}_{-1}e^0$$

$$\searrow$$

$$_{94}Pu^{239} + {}_{-1}e^0$$

First of all a new atom of uranium, U-239, is formed which is unstable and decays to form Neptunium-239; an electron $_{-1}e^0$ is discarded in the process. The Neptunium-239 is also unstable and decays to form Plutonium-239. It turns out that Pu-239 like U-235 has the remarkable property that when struck by neutrons of the proper energy it, too, will undergo fission. Thus while we are losing U-235 we are gaining Pu-239. Since only 1/140 of the uranium atoms in nature are U-235 we see the economic consequence of the plutonium creation. If things could be arranged that for each U-235 atom lost one or more Pu-239 atom was created, we could soon dispense with the utilization of U-235 and would instead "burn up" the 139 times more abundant U-238 instead of the rare and precious U-235. Even if this goal is never achieved, the production of some Pu-239 will reduce the demand for U-235.

The same argument holds for the production of U-233 from thorium. In this case our nuclear reactions are:

$$_{90}Th^{232} + {}_0n^1 \longrightarrow {}_{90}Th^{233} \longrightarrow {}_{91}Pa^{233} + {}_{-1}e^0$$

$$\searrow$$

$$_{92}U^{233} + {}_{-1}e^0$$

If any neutrons over and above the minimum required to keep the chain going, could be diverted into making U-233 we would again lessen our drain on the U-235 stock and replace it by a drain on the much more abundant element thorium. The practicality of the usefulness of these processes remains among the interesting problems of the future.

When an atomic fuel undergoes fission, elements near the middle of the atomic table are formed. For each atom of U-235 which is destroyed two new lighter atoms are created. Some of these will have a low cross section for absorption of neutrons. Others will have larger values and will act as parasites in removing neutrons from the pile. Thus in any practical atomic "furnace" the waste products must be removed. In the Hanford Plant the problem was solved by removing the canned uranium slugs at regular intervals, dissolving the contents by a laborious chemical process, and separating out the uranium and plutonium for further work. This might be a fairly straight forward operation were it not for the fact that the fission products are so strongly radioactive that all

chemical manipulation had to be done in batch processes by remote control behind thick concrete shields. The replacement of the batch handling by continuous methods should be a challenging problem to the engineer and would do much to lower the cost of atomic energy.

We have already mentioned that different elements interact in different ways with neutrons. Consider for example the element cadmium. This element has long been known to be one of the best absorbers of slow neutrons which we have. Cadmium is known to consist of eight different kinds of atoms ranging in mass from 106 to 116 times the mass of hydrogen. Recently it was shown that the abnormally high neutron absorption cross section could be attributed entirely to one type of cadmium atom, the isotope of mass 113, which has an abundance of only twelve per cent. In spite of the fact that cadmium is a very good neutron absorber, we would have one of eight times the absorbing power if this particular isotope could be isolated in quantity.

I mention this fact, not because cadmium is of more or even as much interest in atomic energy work as are other elements, but because it shows so strikingly how some atoms of an element have quite different nuclear properties than others. The nuclear properties which we ordinarily observe for an element are in reality the weighted average properties of the several isotopes which make up the element. Perhaps we shall some time see the day when separated isotopes of any element will be available at reasonable cost. If this ever happens, it will mean having additional building materials for atomic reactors at our disposal because we may then utilize elements not now acceptable because one or more of their isotopes may have objectionable properties.

You have all seen figures showing that if one pound of uranium, an amount about the size of a golf ball, undergoes fission there will be released energy in amount roughly equivalent to 200,000 gallons of gasoline. To the average motorist this would be enough energy to run his car for 200 years. Unfortunately there is a hitch in all this. It has been estimated that in order for it to be safe for a human being to be near an atomic reactor, at least 50 tons of shielding material are required —an amount somewhat more than your car can stand! While this rules out small mobile installations, such a weight of shielding would not be particularly detrimental in stationary units or large propulsion units such as might be used on ships.

Why must such heavy shield be employed? To answer this we must inquire what it is we are shielding against. First of all, there are the neutrons, the particles which make the chain reaction possible. We have already indicated that for efficient operation of the reactor as many as possible of the neutrons should be utilized in producing more fissions. This suggests that, first of all, the pile be surrounded by an envelope of an element which has the property of readily reflecting neutrons without absorbing them. While such an envelope will help reflect a fair proportion of the neutrons which would ordinarily escape back into the pile, it still would permit a large number to leave. Thus to protect

personnel, additional neutron absorbing material is required.

Many of the fission fragments formed are highly unstable and decay to form more stable atoms. In the process gamma rays are emitted. These, like x-rays, are electromagnetic in character but because of the higher energy are more penetrating. Like x-rays, they are absorbed most readily by the heavy elements. In practice concrete has been used as an absorber for both the neutrons and the gamma rays.

In this brief discussion I have touched on only a few of the problems associated with the atomic processes taking place. I have not even had opportunity to discuss the very interesting engineering problem of the regulation of the power output of the reactor by means of automatic adjustment of the position of neutron absorbing control rods in the reactor. This is a large topic in itself.

I have touched on a number of new concepts or terms which form part of the vocabulary of atom workers. I have talked about fission cross sections, absorption cross sections, scattering cross sections, moderators and reflectors. I have not even mentioned such things as radiation stability, homogenous or heterogeneous reactors, power ratings of reactors, any of the special instrumentation required, or the health problems encountered in connection with atomic reactors.

One might summarize what I have discussed by stating that the problem of producing atomic energy is largely one of making efficient use of neutrons. This and the concept of atomic fission are really the only basically new factors with which the engineer must contend. Otherwise the problem of producing atomic energy involves merely modifications of problems which engineers have alfeady solved or will solve in connection with other work. Thus there are many developments which will go hand in hand with those already being carried on in industry, and engineers can make substantial contributions toward making atomic energy an every-day reality by merely extending their scope of operations.

➤ Alfred Otto Carl Nier *was born in St. Paul, Minn., in 1911. After graduating from the University of Minnesota he spent two years as a National research fellow at Harvard. During the second world war he was with the Kellex Corporation, the Atomic Energy Commission and the Office of Scientific Research and Development, doing research on uranium 235 and atomic energy. He has now returned to Minnesota as professor of physics.*

Uranium Minerals Are Black, Yellow and Green

Uranium Prospecting

by Hugh S. Spence

➤ The number of known minerals which contain uranium in some amount is quite large — over fifty species are listed — but the great majority of these are rare and can be considered at present of only mineralogical or specimen interest. In many, also, the uranium present is not an essential constituent, but is more in the nature of an accidental impurity, and the content of the element is so low and so variable that these minerals are of small practical importance as a source of uranium. Even at this time, when there is such a live interest in even low grade uranium ores, such minerals are likely to be of little value as an economic source of the element, and it would be unwise to spend time and money in prospecting for them or in attempting to mine them, if found.

The bulk of the world supply of uranium up to the present has been obtained from deposits of the following minerals:

Pitchblende, and secondary alteration products of

Carnotite - Tyuyamunite

Autunite - Torbernite

Of these, only pitchblende is a primary mineral. The others are of secondary origin, and have been deposited through the agency of circulating waters at or near surface, or are the result of weathering in place of original pitchblende.

Primary Minerals

Primary uranium minerals are dominantly black, conspicuously heavy, and of metallic or sub-metallic appearance.

Pitchblende, the richest and most important, is compact and massive, with no evidence of crystal form or structure. It sometimes is found with botryoidal, or kidney-like, surfaces and a radiated texture. Pitchblende is distinctly a vein-forming mineral, and is usually associated with cobalt, nickel, silver, and copper.

Almost all of the other primary uranium minerals, including *uraninite,* a crystal variety of pitchblende, are confined in their occurrence to granite rocks, more especially to pegmatite, which is a "giant," dyke-forming type of granite in which the chief component minerals, feldspar, mica, and quartz, occur in large crystals or masses. The variety of uranium minerals found in such association is large, and for the most part these are of complex compositions, being multiple oxides of uranium, tantalum, columbium, titanium, iron and the rare-earth elements. They are mostly black to dark brownish-red in color, conspicuously heavy, often of a submetallic appearance, and usually occur in the form of well-developed crystals

up to several inches in length. It is characteristic of such minerals that the rock enclosing them is usually stained or coloured a deep brownish red, and any patches or zones of conspicuously reddish colour in a paler pegmatite groundmass are worthy of examination for the possible presence of uranium minerals. Sometimes, also, small traces of conspicuously coloured canary-yellow or orange powdery crusts of secondary uranium minerals occur surrounding such crystals and serve to confirm their nature. It is not uncommon for pegmatitic uranium minerals to be concentrated in zones containing large nests or aggregates of black mica, and the rock around such mica, as well as the mica crystals or books, themselves, should be given particular examination. The occurrence, also, of a black, coal-like hydrocarbon mineral (thucholite or anthraxolite), which will burn, in a pegmatite is suggestive of the presence of uranium, and this material, itself, often contains a considerable amount of the element.

Complex Composition

As a rule, such minerals occur rather sparsely disseminated in the host rock, though occasionally they form small nests or pockets. Owing to their complex composition, which would make chemical treatment for recovery of the contained uranium difficult and expensive, their variable and often only small content of uranium, and the usually limited quantity present, they can be considered as of only problematic value as uranium ores. However, it is of decided interest to have all new discoveries of such minerals placed on record, in case it may prove desirable to have the occurrences investigated more thoroughly at a future date.

Surface Weathering

Primary uranium minerals are rather prone to alteration and breakdown under weathering agencies, and for this reason they are seldom likely to be found with their fresh outward characteristics preserved in surface outcrops. Many of the species found in pegmatites tend to become externally friable and coated with a rusty crust, when severely weathered, due to oxidation of the contained iron. Pitchblende, as well as its variety uraninite, may weather to a greenish cast, and both are more liable to exhibit characteristic and vividly coloured yellow and orange secondary alteration products.

The foregoing remarks apply more specifically to conditions as they are likely to exist in Canada. In regions of deep weathering, as in tropical countries, it is common for most primary uranium minerals to suffer a complete alteration, in place, to secondary compounds. Certain Madagascar pegmatitic species are usually heavily altered to a yellow powder: the same holds for uraninite from Tanganyika: and at the famous pitchblende deposit in the Belgian Congo, the veins were found to be almost completely oxidized to a considerable depth, with the formation of ore consisting of a wide variety of spectacular and brilliantly coloured uranium compounds.

Possibly owing to ease of weathering, primary uranium minerals do

not commonly form placer deposits, and few instances of such occurrences are known. However, some sections of the Rand banket conglomerate, in South Africa, have been found to carry detrital grains of *uraninite,* or *pitchblende;* and placer deposits of thorianite, a thorium mineral containing considerable uranium, occur in Ceylon. Any beach or river sands containing an important amount of heavy black minerals are worth investigating for the possible presence of uranium/thorium minerals. (See also below, under *Monazite.*)

Since, through surface weathering, pitchblende may break down into a variety of secondary uranium alteration products, all of which exhibit extremely brilliant and characteristic yellow, orange, or green colours, such compounds noted in a vein outcrop, or gossan, offer definite evidence of the presence of pitchblende at depth.

Pitchblende frequently is associated with cobalt-nickel-arsenic minerals, which also weather readily to form characteristically coloured pink (cobalt) and green (nickel) powdery alteration products. The association of a heavy, massive black mineral with such compounds may be taken as strongly suggestive that the former is pitchblende.

Secondary Minerals

As already stated, deposits of secondary uranium minerals have originated through the precipitation of uranium salts derived from primary minerals and carried in solution by surface or circulating waters. The minerals formed in this way are mainly compounds of uranium with such other elements as calcium, copper, lead, vanadium, etc.

Only rarely, as in the case of the famous occurrence in the Belgian Congo, have such minerals been found as a rich replacement in situ of primary ore. More usually, they have been deposited in rather sparse amount on cracks, joints or solution channels in rocks which either originally contained primary minerals or which occur overlying or adjacent to occurrences at depth of such minerals. Occasionally, deposits of this last type have proved rich enough to work for their uranium content, as in Portugal, Russia, and Australia. If carried in solution by surface waters into basins or other favourable catchment areas, uranium salts may be deposited as rich concentrations of secondary minerals. In such event, carbonaceous matter in the form of decaying vegetation (or oil) is particularly favourable to deposition, as in the case of the *carnotite* occurrences in Colorado and Utah, the uraniferous peaty muds of Madagascar, and the lignitic 'kolm' of Sweden.

The bright and extremely characteristic yellow, orange, or green colour of most secondary uranium minerals serves to attract attention to them, and is the most ready means of visual identification. Since such minerals are formed most often in hot, arid, or tropical regions, it is regarded as unlikely that important concentrations of them will be found to occur in a heavily glaciated country such as Canada. Even small traces of them, however, may prove of value as indicating the possible presence of richer primary ore at depth.

Thorium Minerals

It is not uncommon for certain primary uranium minerals, more especially those found in pegmatites, to contain moderate amounts of thorium. Certain varieties of *uraninite,* the crystal form of pitchblende found only in pegmatites, are fairly rich in thorium, but, on the whole, straight thorium minerals which might be regarded as commercial sources of the element are much less common than uranium minerals and only a few are known. Most of even these few are of rare occurence and of only mineralogical interest, and up to the present practically the entire world supply of thorium has been obtained from the single mineral *Monazite.*

Monazite

Monazite is of complex composition, consisting mainly of cerium and other rare-earth elements, with up to 18 per cent of thorium. It is a non-metallic mineral, yellow to reddish brown in colour, conspicuously heavy, and of crystalline character. It occurs as tabular crystals in pegmatite dykes, and as small grains in rocks intruded by granite or pegmatite, but most of the commercial supply is obtained from rich concentrations formed by wave action in beach sands along the coasts of India, Brazil, and Australia. Similar beach deposits are known in Ceylon, Florida, Malay, and the Netherlands Indies, all of which have furnished small quantities.

It is doubtful if occurrences of monazite in rock would be of economic interest at the present time, but such occurrences are worthy of record and might be of value as indicating the possible presence of nearby placer deposits, particularly if they exist in coastal areas.

Any extensive beach sand areas conspicuously rich in heavy black minerals are worthy of sampling for a possible monazite content. The black metallic mineral in such sands is likely to be *ilmenite,* an important ore of titanium, and often associated with it are *rutile* and *zircon,* both valuable industrial minerals.

Other Thorium Minerals

The richest thorium mineral known is *thorianite,* a heavy, black metallic mineral which occurs in small cubic crystals in pegmatites. It is known in commercial amounts only in alluvial placer deposits, and is an exceedingly rare mineral, whose principal source is Ceylon.

Allanite is a complex mineral containing cerium and other rare earth elements; it may carry up to 3 per cent thorium. Its occurrence is confined to pegmatites and granite, and in the former it is sometimes found in very large crystals. Allanite is a heavy, non-metallic mineral, black when fresh, but usually altered externally to a brown colour. An outer brown and friable crust is typical for allanite, and usually serves as a ready means of identifying it. While allanite has not so far come into consideration as a commercial source of thorium, it might serve as such if found in sufficiently rich deposits. For this reason any new discoveries of the mineral are worth placing on record.

Thorium is not precipitated out of solution in circulating waters, as is

uranium, and hence important deposits of secondary thorium minerals are unknown, or are of relatively small importance. Small traces of thorium occur in the sinter of certain radioactive springs in Germany, France, and other countries, and in some cases recovery of thorium has been made from such sources. In view of the relative abundance of monazite, however, this mineral, as well as perhaps other primary thorium minerals, originating in pegmatitic or granitic rocks, is likely to remain, for the present at least, the most important source of the element.

Aids in Identifying Minerals

General, broad information on the character and mode of occurrence of uranium/thorium minerals has been given in the preceding section. Such information will serve as a guide to the main distinguishing features of such minerals and to the type of formation or rock in which they are likely to be found and where they should be looked for.

The following notes in part present a resume of what has already been said, with emphasis on the principal outward characteristics of the minerals, add a few more details that may aid in their visual identification, and, in addition, outline more definite means for determining their nature.

Pegmatitic minerals that contain uranium/thorium, in amounts ranging from small traces to substantial amounts, may exhibit a metallic or non-metallic character and appearance. Often, it may be difficult to decide off-hand into which of these categories a particular unknown mineral should be placed, since many black species appear to be metallic, and only on examination of small fragments under a strong lens or a microscope does their non-metallic nature become apparent. This is evidenced by the fact that thin chips or splinters are translucent, usually exhibiting a characteristic red or brown colour, even though the massive mineral itself may appear opaque.

In general, it may be said that any conspicuously heavy, black or dark-coloured minerals discovered in a pegmatite should be tested for possible uranium/thorium content. Such minerals may be difficult to distinguish visually from *magnetite* and *ilmenite* —both common in pegmatites—or from rarer *tantalite-columbite, wolframite,* and *cassiterite*. Greater weight serves to distinguish them from *black tourmaline,* one of the commonest dark-coloured pegmatite minerals, and from also *hornblende*.

Pegmatitic uranium/thorium minerals usually, though not always, occur as well-formed crystals, which may be of cubic, prismatic, or tabular form. In general, such crystals do not measure much over 3 x 1 inches in size. They may occur as single scattered individuals, but usually they tend to be concentrated in localized groups or zones.

The presence of a bright yellow or orange crust of powder surrounding a dark mineral is almost conclusive evidence that it contains uranium;

and small plates or scales of a yellow or emerald green colour on cracks and joints in a rock are a useful indicator of nearby primary uranium ore.

In dykes composed of pink or red feldspar, the colour of the spar around uranium/thorium minerals is usually of a conspicuously darker brick-red shade; in white feldspar dykes, such minerals often cause a brownish or black discolouration in the enclosing rock.

A conspicuous radial fracturing of the feldspar or quartz surrounding a mineral inclusion in pegmatite rock is also often a useful indication that the inclusion contains uranium/thorium. *Cyrtolite*, a variety of *zircon*, which often contains small amounts of uranium/thorium, is particularly prone to exert a pronounced shattering effect in its host rock, and even small crystals may give rise to strong cracks radiating outward several feet from them.

Pitchblende

As already stated, pitchblende is the only uranium mineral known to occur in the form of definite veins or lodes. It may be difficult to identify with any certainty by its outward characteristics; when relatively pure, however, its exceptional weight serves to suggest its nature. The absence of any indications of crystalline or grain structure, or of cleavage, is helpful, the mineral breaking with a smooth, irregular, fracture and having a dull, somewhat greasy or pitchy appearance or lustre. It sometimes occurs in botryoidal, or kidney-like masses, or crusts, which under a lens are seen to have radiated structure. In this last form, pitchblende somewhat resembles hematite iron, but it may readily be distinguished from hematite by the black or greenish black colour of its streak or powder, which for hematite are a strong red.

Secondary Minerals

Secondary uranium minerals are those formed by the alteration of primary species by weathering or other natural agencies. They may be found replacing the original minerals in situ, but more commonly have been precipitated out of solutions derived from such minerals.

Deposition may have occurred adjacent to the primary source, on cracks and joints in the enclosing rock; or the dissolved salts may have been carried considerable distances by circulation or surface waters, with the formation of rich concentrations in certain favourable areas. The *torbernite-autunite* deposits of South Australia and Portugal are examples of the first type of deposition, and the second type is represented by the *carnotite* occurrences in Colorado and Utah.

As a general thing, a tropical, or a hot and arid, climate is necessary for the formation of important deposits of secondary uranium minerals, and it is unlikely that occurrences of this nature will be found in Canada, where recent glaciation has removed much of the original surface. However, such minerals are important in that they may serve, even in small traces, as indicators of the possible nearby presence of primary ore, and accordingly they are briefly mentioned here.

The only two species commonly exhibiting crystal form are the so-called 'uranium micas,' *torbernite* and *autunite*. These occur in small brittle,

cleavable plates which for *torbernite* are of an *emerald green colour*, and for *autunite* are *bright lemon yellow*.

The other species for the most part occur as either powdery coatings or soft massive material made up of exceedingly fine particles. Intense and vivid colours, in shades of bright yellow, orange, and green, are the chief distinguishing features of such minerals and serve at once to attract attention to them. Most of them are salts of uranium and various other metals, and a large number of such minerals are known.

Mode of Occurrence

Summarizing what has been said above, the following are the main points to be noted in connection with the mode of occurrence of uranium minerals.

Broadly speaking, the occurrences may be divided in the following three main types:

(1) Individual crystals, or nests, pockets, or similar aggregates of crystals—usually of small size and extent—sparsely and irregularly scattered through dykes of *granite pegmatite*. The variety of uranium minerals occurring in this manner is large, and embraces a large proportion of the known species.

Distinguishing characteristics of such minerals are black colour, metallic appearance, heaviness, and good crystal form.

(2) *Veins, or lodes,* of similar character to the general run of those of other metallic minerals such as zinc, lead, copper, etc. *Pitchblende*, the richest and commercially the most important ore of uranium, is the only primary uranium mineral that occurs in deposits of this type. It may be the dominant mineral, or, as is sometimes the case, be in the nature of an accessory in veins of other metallic ores, notably those of silver, cobalt, and nickel. Pitchblende is characterized by black colour, metallic appearance, greasy or pitchy lustre and dense, massive texture. It never exhibits crystal form, but sometimes occurs in layers or bands having botryoidal or kidney-like surfaces.

(3) Deposits of a *bedded, replacement, or stockwork* character, in which the uranium minerals are a minor constituent of secondary origin and nature and have been emplaced through the agency of surface or circulating waters. Occurrences of this type may be found in both sedimentary and igneous (granitic) rocks, and usually they carry little, if any, trace of primary uranium minerals.

Secondary uranium minerals found in such deposits are characterized by vivid and brilliant colours in tones of yellow, orange, or green. They are usually in the form of soft powder, crusts, or tufts, occasionally being more massive. They seldom exhibit distinguishable crystal form, except in the case of the two commoner species, *torbernite* and *autunite*, which occur in small well-developed thin plates.

Radioactivity Methods

All minerals containing uranium/thorium are radioactive; that is, they emit energy in the form of spontaneous radiation, and this may be detected by several fairly simple means. It is not possible, however, to distinguish between the emission from the two elements except by precise

laboratory methods. Close geochemical affinity, also, exists between the uranium and thorium, and many minerals containing either element—more especially the pegmatitic species—frequently carry the other as well, in which case the radiation is of a dual nature, and may lead to wrong conclusions being drawn.

Photography—One of the simplest means for detecting radiation from minerals is to place the specimen on an ordinary photographic plate or film in a light-tight box and allow it to remain undisturbed for about 36 to 48 hours. On developing the negative, any marked uranium/thorium content will be evidenced by a distinct image, or auto-radiograph of the specimen. Intensity of such image, or self-photograph, is a rough measure of the degree of radioactivity of the mineral, and thus of the amount of uranium/thorium present. This amount, in turn, governs the time of exposure required to produce a well-defined picture. To avoid possible misleading effects due to pressure or chemical action on the photographic emulsion, it is sometimes advised to interpose a thin sheet of paper between the specimen and the film. Production of a smooth face on the specimen by sawing or grinding is advantageous and results in a much clearer and more defined image being formed.

Recent refinements in the making of radiographs of mineral specimens employ a special type of light-desensitized film. This distinguishes between uranium and thorium radiation, when both elements are present, by the relative intensity of the image.

Visual—For many years, a simple means of detecting radioactivity in minerals in the field was by the use of a small pocket device known as a *spinthariscope,* or *scintilliscope.* This consists of a short brass tube provided with a cap bored with a small hole in which a magnifying lens is inserted. Below the lens is cemented a small square glass prism, the lower end of which is coated with zinc sulphide powder. If a small fragment of strongly radioactive mineral is held close to this coated surface, some of the radioactive particles emitted impinge on the grains of powder and cause a succession of momentary flashes of light, readily seen through the lens. For best effect, it is necessary to conduct the experiment in a dark place, and to have the observer's vision thoroughly adjusted to darkness for a period of several minutes.

One of the most reliable and widely-used instruments for detecting and measuring radioactivity has long been the *gold-leaf electroscope.* This makes use of the property possessed by radioactive materials of releasing the electrical charge on two small strips of gold leaf through ionization of the air in a small chamber in which they are suspended. By comparing the rate of discharge effected by a measured quantity of powdered and carefully sized material made from an unknown sample with that produced by a similar amount of a standard of known composition, a fairly close and rapid estimate of the degree of activity, and hence of the uranium content, of the test sample can be made. By such means, a great deal of time-consuming chemical analytical work can be eliminated, particularly in

mills and refineries engaged in producing and treating uranium ores. Any thorium present in the test samples of course destroys the efficiency of the method, since thorium is much more active than uranium. For reliable results, the electroscope requires to be employed in a laboratory and is hardly suited to field use.

It is sometimes stated that the portable *ultraviolet light lamp* is a useful tool in prospecting for uranium minerals. This is true to a limited extent only, since only certain of the secondary species, and none of the richer primary minerals, exhibit any fluorescence under ultraviolet light, whether short or long wave. The utility of the lamp, therefore, would be confined to a few fluorescent secondary minerals, only one of which—*autunite*—has so far been found to occur in sufficient quantity to be of any particular economic interest. Accordingly, for practical purposes, prospecting for uranium mineral deposits by fluorescent means is not to be recommended, particularly as we now have a much more simple and practical tool for detecting even small traces of uranium/thorium minerals in the instrument described below.

Electronics—The above-mentioned, and, by comparison, relatively crude means of detecting or measuring radioactivity in minerals or other substances have more recently been supplanted by much more delicate and precise methods provided by an instrument known as the *Geiger counter*. This is a device employing radionic principles, whereby radioactive emission can be directly registered, measured, and recorded, either in the form of sound or in other ways.

For field use on minerals, either broken out as specimens or in place, small portable, light-weight units, equipped with dials, ear-phones, or built-in amplifiers, have recently become available and are proving of considerable value to prospectors engaged in a search for uranium/thorium ores.

In its original, rather cumbersome form, the instrument has long been employed with conspicuous success for locating radium lost or mislaid by hospitals and doctors, and numerous instances of recovery of valuable radium from such locations as garbage dumps, incinerators, drains, etc., by its use are on record.

Development of more elaborate laboratory instruments of this type have now reached a stage where, with the aid of known standards, very precise measurements of uranium/thorium can be made, thus dispensing entirely with the need for chemical analysis and giving results in only a fraction of the time formerly required. Even greater refinements are possessed by models capable of registering selectively the radiation from uranium and thorium, thus establishing which element is responsible for the radioactivity of a mineral, and, if both are present, the relative amounts of each.

It might be noted that the portable type of Geiger counter, designed for prospecting use is essentially a detecting, and not a measuring, instrument. It will register even small increases in the radioactivity of minerals and rocks above the normal count, and will indicate either by sound or dial reading whether a specimen or area is "hot." Within limits, it will indicate the *de-*

gree of radioactivity up to a certain point, thus enabling material or ground to be selected for recording and more detailed examination later. It cannot be used, however, to give even a rough approximation of the actual amount of uranium/thorium present, since various factors may confuse the issue.

Portable counters are of fairly rugged construction, and can be packed around with little risk of damage, provided reasonable care is exercised. Details of operation are readily acquired and call for no special skill or training. With a little experience, and with proper recognition of their limitations, they provide an indispensable tool for the prospector undertaking a search for uranium/thorium minerals.

The Canadian Government, through its Bureau of Mines, has issued this information of how uranium minerals occur and how to look for them. Great Bear Lake in northwestern Canada has rich uranium deposits.

State of Knowledge June 1940

1. That three elements — uranium, thorium and protactinium — when bombarded by neutrons sometimes split into approximately equal fragments, and that these fragments were isotopes of elements in the middle of the periodic table, ranging from selenium (Z = 34) to lanthanum (Z = 57).

2. That most of these fission fragments were unstable, decaying radioactively by successive emission of beta particles through a series of elements to various stable forms.

3. That these fission fragments had very great kinetic energy.

4. That fission of thorium and protactinium was caused only by fast neutrons (velocities of the order of thousands of miles per second).

5. That fission in uranium could be produced by fast or slow (so-called thermal-velocity) neutrons; specifically, that thermal neutrons caused fission in one isotope, U-235, but not in the other, U-238, and that fast neutrons had a lower probability of causing fission in U-235 than thermal neutrons.

6. That at certain neutron speeds there was a large capture cross-section in U-238 producing U-239 but not fission.

7. That the energy released per fission of a uranium nucleus was approximately 200 million electron volts.

8. That high speed neutrons were emitted in the process of fission.

9. That the average number of neutrons released per fission was somewhere between one and three.

10. That high-speed neutrons could lose energy by inelastic collision with uranium nuclei without any nuclear reaction taking place.

11. That most of this information was consistent with the semi-empirical theory of nuclear structure worked out by Bohr and Wheeler and others; this suggested that predictions based on this theory had a fair chance of success.

—*Smyth Report*

How One Can Dispose of Contaminated Material

Radioactive Wastes

➤ Radioactive metals which will be giving off deadly radiations hundreds and thousands of years in the future have been brought into existence in concentrated form by man's activities in recent years. We now have the problem of how to live amid such radiation.

Experience with the effects of radiation on human bodies has come from accidental overdoses of radiation from X-ray machines and from radium poisoning during the fifty years that these sources have been in existence, and from the recently recognized levels of cosmic rays to which we have been exposed unknowingly all our lives. Between these two extremes lies the safe dosage for workers in atomic energy plants. It was from the beginning a goal in Oak Ridge, Hanford and Los Alamos to keep personnel separated from dangerous amounts of radioctivity. Their health record is excellent.

But as time goes on and use of radioactive materials outside these sheltered communities increases, the problem of what to do with contaminated wastes becomes more acute. The wastes may be in solid, liquid or gaseous form. Their activities may spread from mild to lethal in intensity, from very short to thousands of years in duration. Once induced, nothing can change the life-span of a radioactive element. It can be made harmless only by extreme dilution with inactive material of the same sort. On the other hand, radioactivity is not "catching." It can be induced only by irradiation with neutrons or heavily charged particles, in special machines.

The unique danger from radioactive materials is from the ionizing radiations they give off. Although three kinds of rays, of different penetrating power, are given off, the effects of all three on the body are much the same. It is known that a heavy dose can be tolerated for a short time better than a weaker dose acting for a long period, and that a dose concentrated on a small part of the body can be endured better than radiation of the same intensity acting on the whole surface of the skin. Individuals also are known to differ in the amount of radiation they can tolerate, so that one unit of measurement of radioactivity is the amount that will kill half the population of a colony of living creatures exposed to it for a given length of time.

The amount of radioactivity now available in the world has increased by a fantastic factor since 1940. Up to that time, the most dangerous material, from the standpoint of radiation given off, was radium, an element so rare that fifty years of collecting and isolating it had resulted in only about two pounds for the whole world. Today the nuclear reactors at Hanford turn out plutonium by the pound, with comparable quantities of radioactivity. The burst of one atomic bomb sets free radiation equivalent to hundreds of tons of radium.

Radioactive wastes from industrial plants processing fissionable materials and their products must be studied to determine the individual half-lives of the isotopes given off. Filters, scrubbers and precipitators can be used to remove radioactive dust from escaping gases. Radioactive argon may be left, but, in this case, its half-life is short so it may be allowed to escape with other stack gases, when weather conditions are favorable for it to be carried high and dispersed far and wide. On close, inauspicious days activity of the piles is intended to be shut down.

Radioactivity in liquid wastes can come either from disintegrating substances dissolving in water, as in laboratory wastes or from washing up spilled material, or the solid matter naturally occurring in coolant water can be made radioactive as it circulates through a water-cooled pile. The first case is now taken care of by having a special drainage system for radioactive liquids which discharges in a remote area. The coolant water in the Hanford plant is allowed to "cool" radioactively in special reservoirs until the activity is below a certain amount, before it is returned to the Columbia River.

But liquid wastes are bulky and their safe disposal is a problem studied by people responsible for keeping water supplies uncontaminated. One of the factors in radioactive contamination is that such material may be taken up by living organisms. These organisms may become the food of animals higher in the scale of complexity, and the radioactive material may be thus passed on and concentrated in bone or specialized tissues. If this chain of concentration results in clearing the water of harmful suspended matter, the result is useful. If it results in fish that are dangerous to eat, we have another source of worry. So far, the best opinion is that, even in the lagoon where the Bikini tests were made, radioactive material concentrated in the fishes' bones, to the extent that the skeleton showed up plainly in autoradiographs, but was not present in the flesh to a dangerous degree.

Solid radioactive material may range in size from light, air-borne dust, which can be extremely hazardous, to articles too big to discard, such as the structure of the building housing the project which is responsible for the radioactivity. Some of the new laboratory buildings at Oak Ridge actually have walls of sheet metal which can be taken down if they become too contaminated and set aside to "cool." Burying in the earth or embedding in concrete (a good neutron absorber) are temporary expedients. In some cases, contamination is merely on the surface, and cleaning methods which remove the surface, to which the contaminants adhere, will get rid of the radioactivity in that place. It must be remembered, however, that the dangerous materials are still in existence, and will be until the end of their radioactive lives. Decontamination has merely removed them to another place. They may still have to be disposed of.

Symptoms of Sickness Induced by Radiation

Acute Radiation Illness

From the Sixth Semi-annual Report of the Atomic Energy Commission

➤ ACUTE RADIATION syndrome indicates an acute illness which may end in death or recovery of the patient after a few weeks, or it may result in chronic illness which may be fatal after a prolonged period.

The acute syndrome differs radically from previously known types of radiation injury—such as chronic radiation illness which arises after repeated or continuous exposure to radiation and gradually develops as a lingering illness. Radiation injury to a part of the body may be either acute or chronic, as when burns or ulcers result from misuse of X-ray machines. The ulcerated cancers of the skin which developed on the hands of the old-time radiologists and radium technicians are typical examples of the chronic ailments from this type of injury.

Causes of Acute Syndrome

The acute syndrome indicates a much more extensive and severe ailment than any other of these radiation illnesses. It can be caused by heavy radiation from outside the body, or by a much lesser amount of radiation from certain radioactive substances taken inside the body.

External. A man can suffer an acute radiation syndrome by being exposed to radiation from an atomic explosion, from an unshielded nuclear reactor, from a large quantity of radioactive material, or from an X-ray machine operated too long or at too high energy. If the radiation comes from outside the body, it will produce the acute syndrome only if the rays or particles are penetrating enough to strike deep into the body and damage such sensitive tissues as the marrow of the bones. Fast neutrons can do this, so can gamma and X-rays.

Internal. The acute syndrome can also result from a man taking into his body certain kinds of radioactive material that enter his tissues and bones rather widely and become fixed there. Even a small amount of some radioactive materials will cause as acute an illness as exposure to the radiation from an atomic blast.

The rays or particles also need not have great power of penetration because the material that gives them off already is deep within the body where it can do the most damage. Plutonium, for example, gives off alpha particles which can pierce only a few thousandths of an inch of tissue. But because plutonium lodges in the bone and stays there, it can destroy the marrow that manufactures red blood cells. Similarly, other radioactive materials that lodge in peculiarly sensitive parts or organs of the body can cause severe injury.

Unique Aspects

Heavy exposures to either kind of radiation cause a massive breakdown of the body's tissues, particularly in

certain organs of the body. Since destruction of cells in various tissues reaches its height at different times after exposure, symptoms from these injuries will occur at different times as the illness grows worse. Two features make this type of body damage unique:

Tissue damage. No two organs or tissues of the body suffer exactly the same amount of damage. Lymphoid tissue, bone marrow, the sex organs, and the lining of the small intestine suffer heavy damage. Muscles, nerves, and fully grown bone are not so easily injured. Other tissues, such as skin, liver, and lung, lie in between these extremes.

Delayed tissue death. Unless the radiation has been extremely heavy, cells may not die for hours or days. For a week after skin is injured by X-rays, it may show only a surface reddening and swelling of the underlying tissues. Blistering and loss of dead skin may be delayed for 2 weeks.

Varying Severity

A man suffering from acute radiation illness may have only a few symptoms, real enough to him but undetectable by the doctor. Or he may have a severe general illness that ends in death or in a long convalescence. The total amount of radiation he suffers is, of course, the thing that makes the greatest difference. Other factors that play a big part include:

The dose rate. A heavy dose of radiation delivered at one time will cause much more damage than the same dosage divided up and administered at intervals. A certain degree of tissue recovery may take place in the intervals between such periodic doses.

Type of radiation. Neutrons and alpha particles are more damaging to tissue than are gamma or X-rays, although the nature of the injury is very similar in each case, and alpha particles do not penetrate.

Individual response. Scientists believe some people have more resistance than others to radiation. This is rather definite where small amounts of radiation are concerned and may be true of the dosage necessary to cause death. Laboratory tests have proved, for example, that a dosage of radiation ordinarily fatal to man will kill 8 per cent of a certain very pure strain of mice. To kill all the mice, it was necessary to more than double the dosage. Similarly, with lighter radiation, it was found there was a dosage that would kill none of the mice. As radiation increased, larger and larger percentages of each group of mice died.

Course of Illness

The course of illness in acute radiation syndrome can be described from the case records of a few people injured in radiation accidents, and of Japanese exposed to atomic bombings, where their injuries were uncomplicated by blast damage or flash burns. Only a small percentage of the Japanese in Hiroshima and Nagasaki suffered from radiation illness alone. Basing their report on these records, physicians describe the illness of a typical severely injured patient as going through four phases.

Phase I. Within an hour or so after exposure, the patient becomes nauseated, vomits, and suffers general prostration and weakness. Diarrhea

may occur and his blood pressure may fall a little. In general, the heavier the dosage, the more ill the patient will be. This phase is quite similar to the "radiation sickness" suffered by patients treated intensively with X-ray or radium.

Phase II. After the first onset of the illness, symptoms tend to disappear, and for a period of a few days to several weeks the patient feels less ill. For patients who have suffered the heaviest radiation, this period will be short. Reports have stated that Japanese injured by radiation alone were entirely without symptoms during this time, but the best information is that they were sick people who, because of the emergency, drove themselves to do what had to be done.

Phase III. The illness reaches its height during this phase. Whether or not the patient survives depends on his ability to endure this acute stage. The patient becomes apathetic and develops a fever and rapid heart action. He becomes increasingly weak and loses weight. He loses his appetite, may become nauseated and suffer severe diarrhea which is sometimes bloody. Small hemorrhages may appear in the skin and the gums bleed. In severe cases, infected ulcers may spread throughout the mouth. The hair may fall from the head and body about 3 weeks after exposure.

The slightly injured recover quickly, but those who received a heavier dose of radiation may continue gravely ill for weeks. The most severely injured may grow progressively worse over a period of weeks and finally succumb, or may die within a few days.

Phase IV. Patients who survive enter a convalescence during which a feeling of weakness and fatigue are the outstanding symptoms. It may be months before the patients recover normal strength and weight. The skin hemorrhages disappear and the hair, if lost, gradually regrows. Usually within 6 months, the patient feels completely well. All usual methods of examination indicate that, by this time, the patient is normal. Even examinations 2 years later have revealed no remaining physical abnormalities. Nevertheless, it is too soon to say that survivors will not suffer further ill effects.

Other Reactions

Besides the symptoms described, the acute radiation illness includes damage that can be detected only by laboratory tests—changes in blood cells, in male sex organs, and in the functioning of other organs.

Several symptoms of the third or acute phase of the illness stem directly from injuries to certain elements in the blood. Infections and ulcerations arise because radiation destroys the white blood cells that normally hold bacteria in check. A few days after radiation exposure, the white cells decline and, in severe cases, disappear almost entirely. The skin and gum hemorrhages are seemingly connected with a fall in the number of *platelets* in the blood, since these fragments of bone marrow cells help the blood to clot, although other causes such as an increase in an anticlotting substance that resembles heparin, a normal

blood chemical, also contribute. Platelets begin to decline only after an interval of weeks and, where the patient survives, reappear during convalescence. A third and very serious effect upon the blood, the decline in red cells, causes anemia and contributes to the general weakness and debility so marked in acute radiation illness. The decline of red cells starts immediately after exposure and may continue for months.

Microscopic studies of tissue, amplified by more complete research with animals, indicate these blood changes are caused by radiation damage to the bone marrow and to the lymphoid tissue where these various cells are born. And the injury to tissue, as well as the course of illness in the patient, can be traced to damage to the cells. Radiation causes the cells to swell, disorganizes their structure and stops them from reproducing themselves. The stoppage of cell division occurs immediately after irradiation; structural changes appear more gradually. The most spectacular change is the collapse of certain parts of the cell, and the shrinkage of the nucleus followed by death and disintegration. The interruption of cell division is temporary, but when new cells begin again to divide they often show bizarre changes in their inner structure.

Treatment of Injuries

Scientists have devoted a great deal of experimental work to methods of treating radiation injuries. They have found no practical way to prevent the death of cells or tissues heavily injured by radiation. However, the regenerative powers of the body are very great, and if it can be helped to survive the acute stage of the illness, even the most radiosensitive tissues may be able to resume their normal functions.

Many treatments help the body through the acute stage of the illness. Blood transfusions supply red blood cells. Penicillin limits infections. Certain materials, such as toluidine blue, help to reverse the tendency to bleeding. Physicians also maintain the water and salt content of the patient's body—substances apt to be lost in any serious illness. Maintenance of adequate nutrition, especially of those substances used by the body to manufacture proteins and cells, also are helpful.

Energy of the Electrons

➤ WHEN ENERGY is obtained by oxidation, combustion, explosion, or other chemical processes, it is obtained at the expense of these [electronic] structures so that the arrangement of the electrons in the products of the process must be one of lowered energy content. (Presumably the total mass of these products is correspondingly lowered but not detectably so). The atomic nuclei are not affected by any chemical process. —*Smyth Report*

Sources of Radiation and Tracers of Processes

Isotopes Report Reactions

From the Fourth Semi-annual Report of the Atomic Energy Commission.

➤ ISOTOPES[1] for scientific, medical, agricultural, and industrial use constitute the first great contribution of the development of atomic energy to peacetime welfare. Industrial power from nuclear energy may be a decade or longer in the future and most other applications are still largely speculative. But isotopes produced in the nation's atomic energy establishment at Oak Ridge, Tennessee, are already at work in more than 300 laboratories and hospitals in this country and abroad, adding to man's store of knowledge about himself and the world around him.

Isotopes assist science in two ways: as *sources of radiation* for many potentially important uses including the treatment of disease and as *"tracers"* of processes formerly difficult or impossible to observe. As tracers, they are proving themselves the most useful new research tool since the invention of the microscope in the 17th Century; in fact, they represent that rarest of all scientific advances, a new mode of perception.

Man's conquest of nature has generally followed the pattern of (*a*) observation, (*b*) understanding, and (*c*) control. The microscope and the X-ray machine have brought into view the cells and organs of living bodies, the molecules and crystalline structure of matter. But until recently man's vision has not penetrated into the details of growth and change in the living cell or the intricate chemistry of the molecule.

Now, using tracer isotopes, the scientist and engineer can observe atoms as they take part in basic organic and inorganic reactions, much as though the atoms were visibly tagged or labeled. For the first time, it becomes possible to follow in intimate detail nature's fundamental processes—such processes as:

Photosynthesis, in which green plants use energy from the sun to form

[1] There are different kinds of atoms called *isotopes* in nearly all of the chemical elements (hydrogen, oxygen, carbon, iron, copper, etc.). The atoms of any chemical element are all alike in their chemical behavior—the way they combine to make all material things. Most elements, however, have atoms that are not alike in their nuclear properties. For example, every copper atom has 29 electrons whirling about its nucleus, and it is this number (the *atomic number*) that makes copper behave the way it does chemically. But the nucleus of some atoms of copper contains a total of 63 particles (29 protons and 34 neutrons), while the nucleus of other atoms of copper contains 65 particles (29 protons and 36 neutrons). Since these two kinds of copper atoms have different numbers of neutrons in their nuclei, they have different *atomic weights*. They are the two natural or "stable" isotopes of the element copper.

Copper atoms can be made, in nuclear reactors and in cyclotrons, which have nuclei containing some other number of neutrons than 34 or 36. These artificial nuclei are unstable. Any one of them sooner or later converts itself into a stable nucleus by giving off particles and energy rays. These artificial "unstable" copper atoms are called the *radioisotopes* of copper. The radiations from the radioisotopes of the various elements are all different, but they all are able to penetrate solid matter to a greater or less degree.

sugar, starch, cellulose, and other energy-containing carbon compounds used by man;

Metabolism, in which some of these carbon compounds, taken into the body as food, give the sun's energy to the living cell;

The chemistry of hydrocarbons, in which other carbon compounds—coal, oil, gas—that provide man with industrial fuel energy are processed into gasoline and other materials that serve his purposes.

New as it is, tracer research has already broadened our understanding of these and many other fundamental processes of nature. Already, medical men are profiting from a better understanding of the working of the human body. For the future, it is difficult to forecast the gains that isotopes will bring. They will speed the battle against disease. They will help man to make more efficient use of nature's materials, to grow more food, to produce better manufactured goods —in short, to adapt his environment to his needs.

All told, the 96 known chemical elements have more than 800 isotopes, stable and radioactive. Carbon, for example, has five isotopes; that is to say, there are five different kinds of carbon atoms all chemically the same because their nuclei carry the same electrical charge. Where they differ is in their weight. The five kinds of carbon atoms weigh approximately 10, 11, 12, 13, and 14 times as much as the fundamental hydrogen nucleus. The variation in the numbers of neutrons in their nuclei, which causes these weight differences, is also responsible for differences in stability. Two of the carbon isotopes are natural and "stable," three are man-made and "radioactive."

Stable Isotopes

The two natural isotopes occurring in ordinary carbon are carbon 12 and carbon 13 ("C 12" and "C 13"). Of each 100 carbon atoms found in nature, 99 will be C 12 and one will be C 13. This is true whether you find the carbon in the starch in a potato, the glycogen in the liver, or the coal underground; in the graphite in a pencil, the steel in a knife blade, or the diamond in a jeweler's window.

During the 1930s, physicists succeeded in processing a few of the lighter elements so as to "enrich" them in their rarer isotopes. They produced carbon, for example, that contained 20 per cent and more of C 13, which was consequently slightly heavier than natural carbon, although chemically the same.

The physicist's success in producing "heavy hydrogen," "heavy oxygen," "heavy nitrogen," and "heavy carbon" was welcomed by the biologist. All of these elements enter importantly into life processes. Carbon compounds, for example, not only provide animals with energy but also enter into flesh, and blood and bone.

Yet investigators had always been baffled by such a basic problem as finding out how much of a given batch of carbon atoms taken into a living body went into fat, starch, protein, or intermediary compounds and how much went to build bone, flesh, or blood. By chemical analysis they

could extract, purify, and weigh the quantities of carbon in a dissected rat, but all carbon was chemically alike, so the biologists could not say that this or that portion of the carbon had come from any particular batch of food. In other words, before tracers were available, the biologist found it impossible to observe and understand in detail how carbon or other food elements are used by the body.

Given carbon, however, that was enriched in C 13, he could perform a tracer experiment. Feeding to a rat a sample of sugar made with this heavy carbon, which behaves in the body exactly like any other carbon, he could dissect the rat after a measured interval, extract and purify such samples of carbon as he was able to handle, and learn how much of the sugar "tagged" with C 13 had gone into the make-up of each sample. In many parts of the animal the tagged carbon was too much diluted for analysis, and therefore the picture of its distribution was incomplete. But the availability of the isotope provided what had been totally lacking before: a method of identifying portions of a specific batch of atoms, even after they had gone through chemical changes, and learning something about where and how they had been used by the body at the end of a chosen interval of time.

Radioactive Isotopes

Also in the 1930's, while some physicists were learning to separate (or concentrate) the stable isotopes, others discovered how to manufacture radioactive isotopes that do not occur in nature. C 11 and C 14, for example, are man-made carbon atoms which are just as truly carbon in the chemical sense as C 12 and C 13. But the unnatural number of neutrons in their nuclei makes them unstable. They decay into stable elements (C 11 into boron; C 14 into nitrogen) and in so doing send out radiations from their nuclei.

The radioactive isotope puts nuclear energy at the service of the investigator and thus tremendously increases his power of perception. When tagged with C 14 the batch of carbon in the sugar fed to the rat can be detected in the dissected tissues no matter where it occurs in the body or what chemical form it takes. Minute amounts of the tagged carbon reveal their presence to electroscopes or Geiger counters by the radiation signals they emit. In the typical Oak Ridge shipment of C 14—a millicurie[2] —37 million atoms are distintegrating every second. This amount of C 14 is contained in a mere pinch (one three-hundredth of an ounce) of barium carbonate, the compound in which C 14 is usually supplied to users. Yet, if this quantity were distributed among a million rats, the radioactivity would still be detectable in each. The experimenter therefore may allow for extreme dilution of his tracer material in the processes he studies. In the terms of the scientist the radioisotope offers the same *specificity* as the stable isotope (the means of identifying a specific batch of material); and it adds

[2] A *curie* is arbitrarily taken as that amount of a radioactive material that disintegrates at a rate equal to that of one gram of radium, that is, about 37 billion disintegrations per second. A *millicurie* is one-thousandth (.001) of this amount; a *microcurie* is one-millionth (.000001).

to this an almost incredible *sensitivity*—a sensitivity millions of times greater than any analytical technique has ever before provided.

Furthermore, some radioisotopes have given the experimenter the additional advantage of *detection at a distance* of his tracer material. In qualitative observations he need not always end the experiment—dissect the rat or cut up the plant—to make his observations. Because many radiations penetrate solid matter to a practical degree, it is possible for the scientist to carry on continuous observation of life processes in plants or animals. Radioactive atoms have been called laboratory "spies," since they accompany groups of natural atoms through long series of chemical and biological adventures and report all along the way the whereabouts and the size of the groups of which they are a part.

Generally speaking, the signals sent out by radioisotopes can be readily distinguished one from another. The radiation of C 11, for instance, is very penetrating or "hard," that of C 14 very "soft." The intensity of the radiation of a given element, depending upon the rate at which its atoms transform into the stable state, is directly related to its effective life or "half-life,"[3] to name the unit in which this rate of decay is measured. The half-lives of the elements are determined by their nuclear compositions, and nothing that man does can lengthen or shorten them by as much as an instant. C 11, with its intense radiation, has a 21-minute half-life. This naturally limits its usefulness for most investigations. C 14, on the other hand, has a half-life of 5,100 years. Most half-lives of the radioisotopes lie somewhere between these extremes, although a few, like that of C 10 (nine seconds), are so short as to rule the isotopes out as research tools.

Finally, in addition to *specificity*, *sensitivity*, and *detectability*, radioisotopes offer to scientists today the even greater benefit of unprecedented *availability*. Before the war, cyclotrons produced them in microcurie quantities—invisible to the eye; and some varieties, like C 11, must still be made in particle accelerating machines. But the war-created chain-reacting pile produces C 14 in quantities millions of times greater than had been possible before, and the same is true for most of the important radioisotopes used in research and the treatment of disease.

The scientific and medical work possible with radioisotopes today is limited primarily by the number of trained workers capable of using them.

Projects With Isotopes

Recently several hundred of the users of Atomic Energy Commission isotopes reported briefly to the Commission's Isotopes Division on the projects they now have under way. . .

Projects with carbon 14 are illustrative. All told, those reporting tell

[3] The *half-life* of an isotope is that period in which the radioactivity decreases to one-half of its original value—the period in which one-half of the radioactive atoms will disintegrate. In the next similar period, one-half the remainder of the unstable atoms will disintegrate, leaving one-fourth. In a period equal to three times the half-life, the remaining radioactivity will be one-half times one-half times one-half, or one-eighth.

of 72 different uses of carbon 14, which provide a representative sample of the more than 185 projects now under way throughout the world using this isotope.

Some of the reports tell of investigations of various phases of photosynthesis—of attempts to determine, for example, what compounds are first formed by green plants out of sunlight, water, and carbon dioxide; where these compounds are distributed in the plant; how they are built up into the more complex molecules of the food we eat; which plants tend to produce energy-rich compounds in their early stages of growth (a question of practical interest to cattle feeders); and so on.

At least 40 of the reports recount studies of the way in which these compounds figure in the metabolism of living bodies. These studies are carried on by labeling with C 14 the sugars, starches, glucose, proteins, vitamins, and other substances eaten by men and animals.

Seventeen of the studies are concerned with following the chemical transformations of carbon compounds in industrial processes, such as the "cracking" of petroleum, the processing of metals, and the use of the Fischer-Tropsch process for the manufacture of petroleum out of coal.

A Thousand Projects

Carbon 14 is only one of 100 varieties of radioisotopes now being distributed from the Oak Ridge atomic furnace and accounts for less than one out of ten of the total shipments. Many of the others are of equal or greater importance in particular fields —radioactive iodine and phosphorus, for instance, in medical therapy; radioactive phosphorus, calcium, sulfur, and iron in fertilizer studies; and radioactive phosphorus, sulfur, calcium, cobalt, zinc, and iodine in cancer research. All told, more than 1000 different isotope projects are being conducted today, and they deal, in one way or another, with every important aspect of the physical welfare of mankind.

Pile Production of Isotopes

➤ BROADLY SPEAKING, there are three ways in which neutrons in the pile produce radioisotopes: (1) by splitting atoms of fissionable uranium into new atoms of entirely different elements—fission products, so-called—which are radioactive themselves; (2) by being captured in the nuclei of atoms of special "target material" inserted into the pile, turning them into heavier isotopes of the same element; (3) by altering the electrical charge of the nuclei of atoms of target material, thereby transmuting them into isotopes of a different element.

Uranium fission products removed from the pile contain a great variety of radioactive materials, which—in method (1) above—can be extracted and purified by chemical means. However, the radioisotopes obtained are all those of elements near the center of the atomic scale between zinc (number 30) and gadolinium (number 64). With the exception of iodine 131, these do not now enter

significantly into medical, biological, agricultural, or most industrial processes. Therefore, most of the radioisotopes supplied by Oak Ridge must be prepared by methods (2) and (3). These call for the preparation and pile irradiation of special target materials. Phosphorus 32, a widely used radioisotope, can be produced by both methods and may be used to illustrate.

In the production of phosphorus 32 by "neutron capture," method (2), phosphorus 31, contained in phosphate, is put into aluminum cans which are set in holes in a graphite block and pushed into the center of the pile. Each atom of the stable element phosphorus 31 that captures a neutron becomes phosphorus 32. But not enough neutrons are present in "low flux" piles to convert more than a small proportion of the phosphorus atoms to the radioactive state. Hence the phosphorus 32 is still much diluted with phosphorus 31, and the treated phosphate is not highly radioactive.

In practice, therefore, phosphorus 32 is usually produced by method (3), "transmutation." This process starts with a target element different from the element of which an isotope is desired. Sulfur is the target for the production of phosphorus 32. Bombardment by neutrons in the pile changes the electrical charge of the nuclei of some of the sulfur atoms, and thus transmutes them into phosphorus 32. When the sample has been removed from the pile, the radioactive phosphorus can be chemically separated from the target sulfur. Phosphorus 32 in a very pure form, high in radioactivity, can thus be obtained. Unfortunately many important radioisotopes—those of calcium, iron, and zinc, for instance—cannot effectively be made by transmutation. They can be produced only by neutron capture, and this, as stated above, gives a product low in radioactivity. When a pile of higher neutron flux becomes available, it will be possible to produce radioisotopes of greater usefulness for research.

From the preparation of the target material to the final shipment of the product, the production of radioisotopes demands skilled personnel and special equipment. When the pile is shut down for the removal of the irradiated samples, each member of the team of workers must know precisely his assignment in the operation and carry it out quickly and without error. Geiger counters and other radiation detection equipment must be used constantly to check the radiation present. In subsequent chemical treatment of materials, the work must be carried on behind lead shields, the workers using tongs and mirrors to avoid exposure. Many chemical operations are conducted inside a "hot lab," a room with thick concrete walls in which apparatus is manipulated from outside by remote control devices, the chemist viewing his work through periscopes. Each radioisotope, moreover, is a separate production problem, involving its own combination of requirements—for target material, irradiation time, chemical treatment, safety precautions, and the rigid time limits associated with its inflexible half-life.

Dynamic Life Processes

➤ Tracing life processes by the use of stable and radioactive isotopes, we now have learned that all components of the body—the muscles, bones, and teeth as well as the blood, secretions, and food stores—are in a constant state of breaking down and renewal. The multitude of life compounds involved in this process go through continuous and rapid chemical reactions, many of them reversible. Those not serving at any given moment as part of the fixed structure, and not excreted from the body, are combined into a metabolic "pool" of life ingredients available for use anywhere in the body.

The most surprising fact revealed has been the extreme rapidity with which life processes take place. Experiments with radiosodium provide a measure of their speed. By "tagging" salt (sodium chloride) with sodium 24 and injecting it into the human body, investigators have found that salt is diffused through the walls of the veins, transported to the sweat glands, converted into sweat, and carried to the surface of the body, all in less than one minute's time. Again, it has been discovered that the transfer of fluid in and out of the human veins is so rapid and continuous that it carries back and forth with it 50 pounds of salt, on the average, every day.

Rapid as they are, however, the biochemical reactions which build up and break down living tissue are so delicately regulated that every part maintains its characteristic form and composition, every fluid its particular chemical make-up; and the total volume of all bodily ingredients remains constant. Although metabolic changes are continuous everywhere, the parts of the body, in health, always appear the same. Hence the classic concept of the body as a mechanical engine.

A modern tracer investigator has compared the body, instead to a military regiment, which retains its size, form, and composition while the individuals of which it is composed are continually changing: joining up, being transferred from post to post, promoted, or demoted; acting as reserves; and finally departing after varying lengths of service.

Since the treatment of illness must be based upon an understanding of the normal functioning of the body, the medical implications of the new concept of the "dynamic state of body constituents" are nothing less than revolutionary. Fundamental changes in medical science are certain to result from research with isotopes. But isotopes assist the medical research scientist and the physician in more immediate ways as well. They are the most powerful and searching laboratory tools yet devised for the investigation of the functioning and malfunctioning of particular organs; for studying the action of vitamins, hormones, enzymes, and other biochemical substances; and for testing the efficiency of many kinds of treatments. Furthermore, they are of practical assistance in hospitals for diagnosis and therapy.

Kinds of Tracer Research

Virtually no observation was possible of the mechanisms, reactions, and pathways of elements and compounds in the body before isotopes were available to trace them. The hundreds of different life materials—those built into the structural parts and those in the metabolic "pool"—are indistinguishable as to origin. The almost limitless variations of the basic carbohydrates, fats, and proteins are formed out of relatively few source elements in the diet—carbon, nitrogen, hydrogen, oxygen, phosphorus, sulfur and iodine. Long before isotopes were available, biologists had attempted to trace some of these elements by labeling them with benzene derivatives, dyes, and some identifiable materials, but the very abnormality of the substances used upset the delicate processes being studied and therefore produced confusing results.

Today isotopes provide labels for all the fundamental life elements—labels which the body cannot distinguish from the normal material. Biologists have already used them to trace such a variety of bodily ingredients as: alcohols, amino acids, antigens, bacteria, bile acids, blood cells, carbohydrates, carcinogens, enzymes, fats, fatty acids, hormones, insulin, nucleic acids, penicillin, pharmaceutical agents, proteins, starches, sulfa drugs, tissue fluids and salts, viruses, and vitamins.

So small are the quantities of radioisotopes required for tracer experiments that most of them can safely be employed in normal human bodies. Calcium 45 and strontium 89 and 90, because they have long half-lives and tend to remain in the body, are at present important exceptions.

Isotopic tracers permit two kinds of biological analysis: *qualitative*, in which a particular element introduced into an experimental animal, and sometimes a human subject, may be followed wherever it goes, whatever chemical form it takes, and *quantitative*, in which the amount of the tagged element in a tissue or fluid may be measured with unprecedented delicacy. When these two methods are combined, formerly insoluble biological problems, such as the rate of turnover of nutrient materials in different kinds of cells, may be successfully tackled.

Separation of Isotopes

➤ It is well known that the molecules of a gas or liquid are in continual motion and that their average kinetic energy depends only on the temperature, not on the chemical properties of the molecules. Thus in a gas made up of a mixture of two isotopes the average kinetic energy of the light molecules and of the heavy ones is the same. Since the kinetic energy of a molecule is $\frac{1}{2}mv^2$, where m is the mass and v the speed of the molecule, it is apparent that on the average the speed of a lighter molecule must be greater than that of a heavier molecule. Therefore, at least in principle, any process depending on the average speed of molecules can be used to separate isotopes.

—*Smyth Report.*

Radioactive Particles Can Be Detected on Photographic Plates

Photographing Nuclear Particles

by Dr. J. H. Webb

➤ Special photographic plates are marketed commercially by means of which individual nuclear events and the paths of charged nuclear particles can be registered and viewed with a conventional microscope. The plate is first exposed to particles from a radioactive source, the paths of the particles being marked by a trail of developable photographic grains in the emulsion. After developing, fixing, and washing in conventional manner, the tracks of the individual nuclear particles are viewed under a microscope.

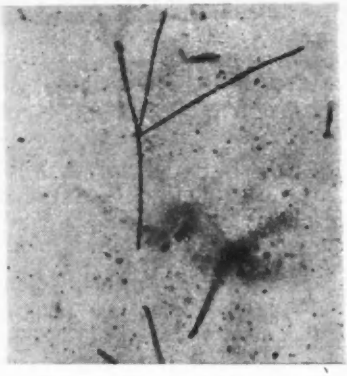
A number of simple, but illuminating, experiments can be carried out with these plates that might be suitable for a high school class in physics. Some of the simpler types of experiments that could be carried out for this purpose are described below.

Experiments

1. *Tracks of Alpha Particles.* A very straightforward experiment consists in exposing the photographic plate directly to a weak source of polonium and registering the alpha particle tracks. Polonium is a naturally radioactive material giving up mono-energetic alpha particles of 5.3 million electron volts energy. These alpha particles have a path in air of about 4 cm. and will travel in straight paths in the emulsion leaving a trail of developable grains of 22 microns in length. A one-microgram source of polonium plated on a thin metallic base, if placed within 1mm. of the photographic emulsion for 30 minutes, will give numerous alpha particle tracks that can be viewed under the microscope with a magnification of 400 times. An illustrative picture of alpha particle tracks obtained in this way is shown in Figure 1.

2. *Thorium Star Tracks.* Another interesting experiment consists in registering several alpha particles emanating from a single thorium atom during the process of disintegration of this atom. The thorium atom disintegrates in steps by giving up a series of alpha particles and electrons over a long period of time. In this case, instead of the alpha particles entering the emulsion from an external source, the radioac-

1. Alpha particles *given off by a weak polonium source, exposed to the photographic plate for 30 minutes, show up like this after the plate is developed and magnified 400 times.*



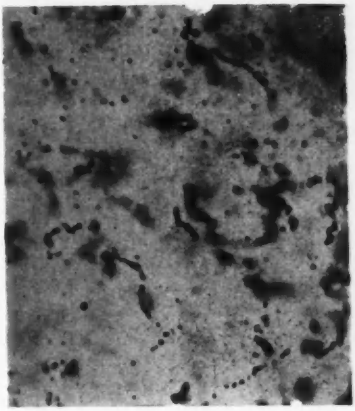
2. THORIUM STAR *tracks appear on plates which have been soaked in a solution of a thorium salt, dried and put away in the dark for about a week before development.*

tive thorium is incorporated directly in the emulsion. The photographic plate is soaked in a solution of thorium acetate or nitrate (0.1 per cent by weight) for a period of 10 minutes, rinsed, dried, and then set aside in the dark for a time of about one week. It is then developed, fixed and washed in the regular manner. Such a plate is found, on microscopic examination, to contain throughout its depth numerous "radio thorium stars." An example of such a star is shown in Figure 2. The energies of the alpha particles given up by the disintegrating thorium atom are well known, ranging from 4.0 to 10 million electron volts. By measuring the lengths of the tracks of the alpha particles in a particular star, it is possible to determine the parent nucleus from which each alpha particle is emitted and hence the time order in which they occurred.

3. *Testing Radioactive Minerals.* An experiment that can be carried out readily with simple equipment is the registration of nuclear particles from radioactive minerals. A photographic plate placed within 1 mm. of a radioactive mineral, such as zircon, carnotite, monazite, or pitch blend, will register the tracks of alpha particles from the radioactive atoms contained in the mineral. This is a technique being used today in the exploration for uranium-bearing ores. Because of the short paths of alpha particles from naturally radioactive materials, only those radioactive atoms in the very surface of the mineral are effective. Therefore, the exposures must be extended to one or two weeks usually to obtain enough tracks after development for easy observation.

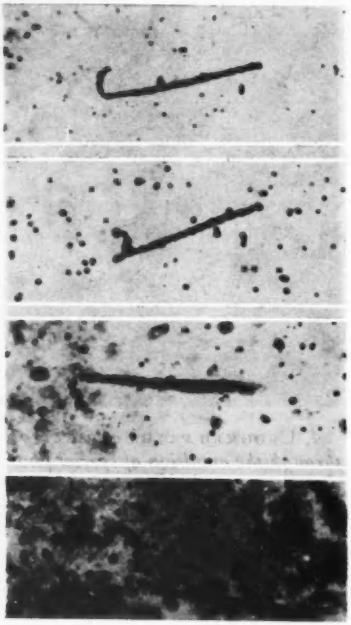
3. PROTON TRACKS *after a sixteen hour exposure, from a polonium source through an aluminum window.*

4. *Registration of Proton Tracks.* Present-day nuclear particle plates will register the paths of protons (nuclei of hydrogen atoms) as well as alpha particles, though the tracks are usually somewhat lighter in grain density. The usual method of obtaining proton tracks in an emulsion is to bombard the plate directly with protons from one of the high-energy accelerators such as a cyclotron. In absence of such equipment, however, there are other methods of obtaining proton tracks. For example, if a concentrated polonium alpha particle source (about 5 millicuries) is covered with a 0.05-mm. thickness sheet of aluminum foil, the alpha particles will impinge upon the aluminum atoms and produce protons. The yield is low, there being produced only about one proton for each 100,000 alpha particles. However, if the polonium source, aluminum foil, and photographic plate are placed close together, enough protons can be obtained to give a number of proton tracks in the emulsion. Proton tracks obtained in a 16-hour exposure in this way are shown in Figure 3. These tracks were obtained with a polonium source of 10 millicuries, coated on a 5-mm. diameter copper disc, with the alpha particles impinging upon an aluminum foil window .025 mm. thick, and $\frac{3}{8}$ inch in diameter, at a distance of 2 mm. from the polonium source. The photographic plate was placed in a sloping position 3-5 cm. from the aluminum foil. The energies of the protons to be expected range from 1.2 to 2.5 million electron volts on the average; however, it is possible to obtain tracks in this way for protons up to a maximum of about 6 million electron volts.



4. CROOKED PATHS *of electrons through the emulsion of special photographic plates made for the purpose. Radioactive material on the luminous figures and hands of a watch or clock will give off enough electrons to show tracks like this.*

5. *Registration of Electron Tracks.* Nuclear track plates are now available that will register the tracks of electrons, though somewhat higher sensitivity emulsions are required than those used for the foregoing experiments with alpha particles and protons. Electron tracks in emulsions can be obtained in a variety of ways. a) The most direct method is to place one of the nuclear track plates directly in the electron beam of an electron microscope. Exposure to electrons of 25 to 50 kilovolts energy will result in many tracks in the emulsion that may be viewed after processing in the usual way. b) Another method of obtaining electron tracks is to expose the photographic plate to x-rays of 50 to 200 kilovolts energy from a conventional



5. NUCLEAR TRANSITIONS *among the decay products of uranium produce these tracks.*

x-ray machine. Exposures should be given long enough to produce a barely visible density after development. The plate can be exposed inside its wrapping and cardboard container since the x-rays will penetrate these light materials. The electrons are produced in the emulsion by photoelectric ejection of electrons from the atoms absorbing the x-rays. The electrons in turn travel in crooked paths through the emulsion and leave a trail of developable grains in their wake. Tracks of electrons obtained in this way are shown in Figure 4. c) Electron tracks can be obtained by exposure of the photographic plate to a naturally radioactive material such as radium, thorium, or uranium. One simple method of obtaining tracks of electrons is to expose a nuclear track plate to the radioactive numerals on a luminous dial watch or alarm clock. For this purpose it is better to remove the crystal of the clock or watch and place the plate directly in contact with the numerals. The light and alpha particles can be absorbed by interposing a thin sheet of tissue paper between the source and photographic plate.

Exposures

Exposures should extend from 5 min. to 1 hr. depending upon strength of source. The electrons will penetrate the paper to give tracks in the emulsion. d) Lastly, a very nice method of obtaining electron tracks is to record the tracks of electrons from individual radioactive atoms as was outlined for alpha particles in Experiment 2 above. Again, the emulsion is impregnated with uranium or thorium acetate (or nitrate) as described in Experiment 2. After being set aside for a week or two, the plate is developed, fixed, and dried, and then examined for electron tracks. Examples of electron tracks obtained in this way are shown in Figures 5 and 6 for the respective elements UX_1 and thorium. The long heavy track in Figure 5 corresponds to the alpha particle emitted in the transition from UI to UX_1. The light crooked track at the end of the alpha track corresponds to the emission of an electron from the UX_1 atom. Similarly, the crooked track shown emanating from the thorium star in Figure 6 corresponds to an electron emission

during one stage of disintegration of the thorium atom.

It is to be strongly emphasized that experiments which involve the use of radioactive materials constitute a definite health hazard unless the experiments are carried out strictly in accordance with rules for the safe handling of such materials. It is therefore of great importance that experiments of the above described types be carried out under strict supervision and in accordance with proper safety rules such as outlined in the article, "Health Physics," published in *Nucleonics*, Vol. 3, p. 60, 1948.

Photographic Plates for Use in Nuclear Track Work

The types of photographic plates for carrying out the above experiments are available from the Eastman Kodak Company and can be purchased from regular Eastman Kodak Company dealers authorized to sell industrial products. For the above experiments, two standard types of plates are recommended. These are:

1) The Kodak NTA plate, size 1" x 3", thickness 25 microns, packaged in 1-dozen lots. These plates will register alpha particles from all naturally radioactive materials and protons up to 5 million electron volts. These plates are processed as follows: Develop for 2 minutes in Kodak D-19 developer at 68° F. temperature, wash for 10 minutes in running water at the same temperature, fix in plain 30 per cent hypo for twice the time for the plate to clear. Plates nos. 1, 2, 3, and 4 are recommended for the experiments.

2) The Kodak NTB plate, size 1" x 3", thickness 50 microns, packaged in 1-dozen lots. These plates will register, in addition to alpha particles and protons, electrons up to 100 kilovolts energy. These plates should be processed as follows: Develop in Kodak D-19 developer for 15 minutes at 68° F., wash for 10 minutes in running water at the same temperature, fix in plain 30 per cent hypo for twice the time to clear. Plates nos. 5 a, b, c, and d are recommended for the above outlined experiments.

6. Electron emission *from disintegrating thorium produced this typical star, with the electron's crooked path straggling down the plate.*

➤ Julian Hale Webb *was born in Anderson, S. C., in 1902. After graduating from Clemson College he did graduate work at the University of Wisconsin. He was with the Manhattan District during the war. He is now a physicist with the Eastman Kodak Co.*

Gas Ionization, Photography Reveal Radiation Phenomena

Radiation Detection Instruments

by H. D. Le Vine

➤ The basic methods for alpha, beta and gamma measurements were worked out many years ago and actually few radically new methods have been devised, except that the work of physicists and engineers in the Atomic Energy program has rapidly advanced instrument and circuit design so that present day equipment is reliable, sturdy, and will retain calibration in a satisfactory manner.

The most commonly used devices today are those which depend upon gas ionization phenomena or the blackening of photographic emulsions. Up to the present time workers detecting radioactivity have devised methods that can measure physical change which results from the bombardment of gases, liquids and solids by radioactive particles. Gas ionization has been measured by electroscopes, electrometers and vacuum tube circuits. Temperature rise due to energy absorption has been measured by bolometers and similar instruments; fluorescence by photocells and light meters; the blackening of photographic emulsions visually or by a densitometer; the ionization within diamonds and other crystals by counting circuits or observation of color change within the crystal.

Alpha, beta, gamma, neutron and other radiations differ in their capability to penetrate matter and to create ionization in matter. The degree of ionization that a radiation can produce depends, to a great extent, upon the velocity at which the particle is traveling or its ability to knock electrons or protons from matter that it strikes.

Alpha and Beta Particles

The alpha particle is a positively charged helium nucleus, i.e., one that has lost its two planetary electrons. When they are slowed down, alpha particles regain the two missing electrons and then become helium gas. Even the most energetic alpha particles can travel only 8 or 9 centimeters before they are completely stopped by air. A thin sheet of paper will block their passage. These particles have rather high energy, which may be as much as 7 M.E.V., and may produce approximately 200,000 ion pairs before they are stopped. The specific ionization becomes markedly greater as the alpha particles slow down. An alpha particle with a range of 7 centimeters will produce an average of approximately 2400 ion pairs per millimeter of air traversed at 15° C. and 76 centimeters pressure. An alpha particle of 3 centimeters range will produce an average of approximately 2900 ion pairs per millimeter of air traversed and one of approximately .5 centimeters range will produce an average of about 6000 ion pairs per millimeter of air traversed.

Beta particles are high speed electrons that sometimes have energy levels up to about 10 M.E.V.; generally the beta particle energy level is less

than 3 M.E.V. A beta particle with a 3 M.E.V. energy level will travel at very nearly the velocity of light and will produce about 4 ion pairs per millimeter of travel, whereas a 3 M.E.V. alpha particle will have a speed 1/25 that of light and will produce 4000 ion pairs per millimeter of travel. It is obvious that an alpha particle will produce much greater ionization than a beta particle, but, on the other hand, a beta particle with a 3 M.E.V. energy will travel about 13 meters through air before it is stopped, compared to 1.7 centimeters for an alpha particle starting with the same energy level. The beta particle does not travel in a straight line but straggles, wandering in its path.

Gamma Radiation

Gamma radiation is electromagnetic in character and has much greater penetration through matter than either alpha or beta. High energy gamma can penetrate more than a foot of lead, while low energy gamma is very much the same as the soft x-radiation generated at 200 kilovolts or less, which can penetrate only about 3/16" of lead. Gamma radiation itself does not ionize, but, in striking matter, its behavior is identical to the action of light on a photoelectric surface; photoelectrons are ejected. The gamma radiation is measured as a discrete amount of energy, the photon, and each photon will eject one or more photoelectrons from matter that it strikes, whether the matter be gas, liquid or solid. These photoelectrons, with a somewhat lower energy level than the gamma photon that created them, ionize matter and thereby produce effects equivalent to other particles.

Neutrons

Neutrons are uncharged particles and were not originally recognized as they produced no direct ionization. On striking materials than contain hydrogen, lithium, beryllium and boron, protons are ejected from the nucleus. These protons, which are positively charged particles, can ionize gases, liquids and solids. When detected, they may indicate the presence of neutrons.

We speak of fast, slow and thermal neutrons. Fast neutrons may have an energy level of about 50 M.E.V. or more and the protons ejected will have an energy level of about 10 M.E.V. Slow neutrons are those whose energy levels are about a few thousand electron volts. Thermal neutrons have an energy level of approximately .028 electron volts.

Neutrons may be generated when alpha radiation impinges on lithium, beryllium, boron, deuterium and other materials. On the other hand, when slow neutrons impinge on lithium and boron, they may cause the emission of alpha particles.

In the methods of measurement of radiation by gas ionization, one hears of Ionization Chambers, Proportional Counters and Geiger-Mueller Counters. Each of these represents a different operating portion on the curve that relates the degree of gas ionization to the voltage between electrodes of a given configuration in the ionizing medium. When radiation ionizes gas molecules, electrons and positive and negative ions are formed. Since the negative ions which are formed almost instantaneously recombine with the nearby positive ions, negative ions

cannot be collected efficiently and therefore we generally speak of positive ions and electron collection only.

The positive ions, being of great mass, move slowly in the electrical field in comparison with electrons, and thus, when it is possible, every effort is made to collect electrons rather than positive ions, except when electron collection may give an inaccurate result due to other ionizing radiation which may be measured.

Gas Ionization

To explain the gas ionization phenomena, we can consider a device which consists of a cylindrical cathode, a central wire anode, and a sensitive means of measuring voltage changes that appear on the anode. With no voltage between electrodes, any voltage changes appearing in the anode will be due to electrons striking the wire in a random fashion.

With the application of low voltage gradients to the wire, the electrical field in the space between the cathode and the anode will cause electrons to be accelerated toward the positively charged anode wire. The electron will give up its charge at the wire and create a voltage pulse that is directly proportional to the number of electrons arriving there and to the capacitance of the system since each electron will carry approximately 4.8×10^{-10} e.s.u.

Since the average alpha particle will create about 100,000 ions, the average beta about 1000 and cosmic radiation about 300 per 10 centimeters of path, the ratio of pulse heights developed in an ionization chamber will be about 3:10:1000.

Avalanche Effect

When the voltage gradient is raised and the conditions inside the gas system are correct, then each electron will be accelerated and will ionize additional gas molecules due to the high electrical field gradient. This ionization creates an avalanche effect, limited only by the positive ion sheath that tends to surround the anode wire. The pulses generated are still proportional to the intensity of the incoming signal.

Due to the cascade effect of the avalanche, the proportional counter will multiply each ionizing event and therefore this multiplication will result in a much higher pulse output for an ionizing event than would be expected in an ionization chamber where no amplification takes plaee. The difference in pulse heights is called gas amplification and may be a figure with a value of several thousand.

When the voltage gradient is increased still further, the avalanche of ionization is no longer impeded by the positive ion sheath, and, generally, all the pulses that result are about the same height. This Geiger counting region, in contrast to the ionization counting region and the proportional counting region, when expressed in graphical form, plotting counts per minute versus impressed voltage, gives a fairly horizontal plateau that may extend as much as 300 or 400 volts. Beyond this plateau amost continuous discharge takes place without the presence of radiation.

Method of Detection

The choice of the detecting method used—ionization chamber, proportional counter or Geiger counter—is determined by what the instrument is

expected to do and the sensitivity of the measuring device which is to be used in conjunction with the detecting device. While the Geiger counter cannot distinguish between beta, gamma and cosmic radiation, the ionization chamber and the proportional counter can conveniently distinguish any of these from each other or from alpha.

Since an ionizing event may be repeated within a few microseconds, the system must be able to detect and measure a second event without interference from the operation of measuring the first event. This requires a system with a very short electrical time constant. The resolution of a detecting circuit is its ability to distinguish between two ionizing events that occur within a very short time of each other. This resolution is a combination of several factors, including the electrical capacitance of the circuit and the resistance between the electrodes. The time constant of the circuit is a product of the capacitance and the resistance; since very high resistance may be used occasionally, the time constant may be in the order of several seconds or minutes.

Since very small currents appear at the collecting electrode of ionization chambers, the measuring device should be either an electroscope, an electrometer or a vacuum tube circuit operating with low current drain on the measuring chamber. The vacuum tube circuits now available nullify the time constant of the ionization chamber circuit in spite of the high input resistance used. A small portion of the signal is fed back to the input circuit, which reduces the effective time constant to values permitting reasonable measuring accuracy.

Disintegration Count

When radioactive disintegration proceeds, the process is not one in which a uniform rate of disintegration results; rather, the fluctuations are statistical and the indicating device generally gives a reading that must be interpreted. If a low count is to be taken where a high background count exists, due to either contamination or natural radioactivity present, the total number of counts must be adequate to permit some statistical evaluation to be made. On the other hand, when one is counting material with high activity, the background could be ignored and the counting time reduced, although the total number of counts recorded should be adequate.

As a typical example of a low background count, procedures have been developed to permit measurement of the quantity of radon in the expired breath of persons who have ingested radioactive materials. The quantity of radon present in a one liter sample is generally in the order of microcuries. The rate of disintegration of the radon a few hours or more after the expired air sample is taken may be as little as a few counts per minute, and since the background of a counting chamber may be equal to this rate of disintegration, a recorded count must be taken for 8 to 10 hours in order to secure a rate of disintegration to a degree of accuracy consistent with the requirements of the determination.

Window Density

Because the windows of the measuring device may absorb all the radiation before it can enter the measuring area, in the case of the alpha and beta radiation, extremely thin window sections

must be employed. Such windows are generally described as having a density of "milligrams per square centimeter" rather than as having a thickness and a density of material. Materials such as mica and low density plastic films less than .0006" thick are also in common use. Glass wall counters .0006" thick are also commercially available. Since the absorption of alpha and beta particles is mainly by collision with matter, a greater weight per unit of area would indicate the presence of a more massive quantity of matter to obstruct the passage of particles to be detected. With gamma and x-radiation the absorption is by K electron capture of the photons. The higher the atomic number of the material acting as an absorber for gamma and x-radiation, the greater is the absorption coefficient.

For the monitoring of personnel it is desirable to have the ionization chamber attached to the person's clothing. Considerable development has been made in pocket ionization chambers approximately the size of a fountain pen. These chambers are charged and read by an external device. They are very rugged and consist of a grounded cylindrical conducting electrode and a highly insulated coaxial wire. The chamber has a capacitance of a few micromicrofarads; the wire is charged up to about 150 volts. When radiation enters the chamber, the ionization that results reduces the voltage in proportion to the quantity of radiation. After the predetermined exposure time—one or more days, usually—the chamber is returned to the measuring circuit. The voltage change, based upon previous calibration, indicates the total dosage directly in roentgen units.

The pocket dosimeter is based essentially upon the same principle except that instead of a central insulating wire, a small electroscope and a capacitance is installed within the cylindrical electrode. The total charge and any subsequent voltage change are then read directly by observing the shadow of the quartz fiber of the electroscope on a scale which can be illuminated by placing the instrument so that a reasonably strong light shines into one end. An external charging box is required to bring the chamber up to operating voltage. These chambers are calibrated with gamma radiation and generally the scales are accurate within about ± 10%.

Recently pocket size radiation detection units have been developed using Geiger-Mueller counters that require a very low voltage polarizing source. These devices will sound an alarm after having received approximately 50 milliroentgens.

One of the more successful commercial versions of a portable electroscope ionization chamber unit is the Lauritsen-Wollans instrument, which consists of a thin wall ionization chamber having discriminating devices to differentiate between alpha, beta and gamma, a time indicating device and a quartz fiber electrometer. The instrument is very light and is highly favored for field survey work.

Cutie Pie

The Cutie Pie is a hand-held survey meter than can distinguish between beta and gamma radiation and is used for checking high intensity sources. Its full scale range is 100 milliroentgens per hour for the most sensitive setting in the commercial model. This instru-

ment has, however, been made with full scale sensitivity of 50 milliroentgens per hour.

The Zeuto is an excellent lightweight instrument for the detection of low level radiation. The electronic circuit consists of three tubes, two in a bridge circuit and the third in a feedback circuit to reduce the input time constant. This rate meter retains its calibration reasonably well.

The Zeus is similar to the Zeuto but has considerably less sensitivity. It also has the added feature of sliding aluminum and lucite screens, which allow differentiation between alpha, beta and gamma.

The family of proportional counters includes several partable and semi-portable types. The most successful design is the Poppy. It can be used in conjunction with any one of a number of chamber designs which may be required for some particular application, such as the counting of alpha particles on the hands, using two flat chambers. Frequently a cylindrical probe is used to measure the alpha radiation present in orifices due to the deposition of dust. It is used mainly to check surfaces such as floors, walls, containers, table tops, etc., for contamination. The proportional counter is difficult to handle because of its instability at the operating point, which is on a steep portion of the characteristic curve. Slight changes in voltage may create large errors in the counting rate; difference of humidity and air pressure will cause the operating point to shift greatly.

Another type counter is called the Walkie Poppy, which consists of a power supply, an amplifier carried on the shoulder of the operator, and a small probe with a thin alpha permeable window on the end of a long cable. The operator uses earphones and can detect a few counts of alpha per minute by means of this instrument.

The Poppies Pop

The Poppies are so named because of the clicking or popping sound heard each time an alpha particle is located. Similarly, each of the instruments in the Atomic Energy Commission program has been coded on the basis of some one of its characteristics. For example, the Chang and Eng is actually a siamese dual ionization unit used for the measurement of neutron flux.

The Geiger-Mueller counter equipment consists of a power supply and a rate meter unit used in conjunction with a probe type Geiger-Mueller counter tube. The instrument is light, portable, and is excellent for low counting rates. It tends to overload as the counting rate increases, but since its general application is for the detection of small quantities of beta and gamma radiation, it has enjoyed very wide use.

The Geiger-Mueller tubes are of interest since their application is considerably greater than just for use as portable probe units. Geiger-Mueller counter tubes are made in a variety of forms; some are cylindrical and require that the radiation impinge at right angles to the axis of the tube; others, used for beta measurements, have their windows placed so that the radiation must be parallel to the axis of the tube; still other types are used for dipping into solutions that are radioactive.

The original Geiger-Mueller counter tubes could not quench their discharge and therefore required external

quenching means. More modern types of Geiger-Mueller counters in general use have vapors added to the noble gas filling. These are capable of quenching the discharge themselves. Since a portion of the organic vapors is destroyed during each quench period, the life of the tube is limited but still is quite adequate for continuous heavy work. These tubes may be used in conjunction with scalers. Scalers are frequently dividing units which record each count and integrate the total number of counts, either as a power of 2, i.e., having scales of 2, 4, 8, 16, 32, 64, etc., or as a decade device indicating the count in uits, 10's, 100's, etc., either by interpolation or by direct reading methods.

The Newest Developments

In addition to the instruments described above, which were largely developed during the years of secrecy at the Atomic Energy plants, a few new kinds of radiation principles have recently come into use. The foregoing article by H. D. Le Vine, reprinted from the February, 1949, CHEMISTRY, *is from the AEC Radiological Laboratory, New York, and was originally presented before the New York Safety Council. Descriptions following are from the Eighth Semi-annual Report of the Atomic Energy Commission, dated July 1950.*

Scintillation Counters

When certain materials are struck by radiations they emit light. A familiar example is the screen used in making fluoroscopic (X-ray) examinations in medicine; another is the television screen. The visible light from the screen in these cases is made up of millions of tiny light flashes, or scintillations. This principle is widely used in the radiation detection instruments called *scintillation counters*, which employ a photomultiplier tube. In these devices, the tiny light flashes resulting from impact of radiations on a fluorescent material may be invisible to the naked eye. But when the light strikes a coated metal surface in the photomultiplier tube, electrons are dislodged. These electrons in turn strike another surface which gives off more electrons for each electron that hits it. By using from 9 to 16 of these metal surfaces in succession, the number of electrons released by each initial scintillation can be multiplied a million to a billion times. The electrical output of this so-called photomultiplier tube is sufficient to register in an electronic instrument.

Scintillation detection instruments are highly efficient and count very rapidly, so that they may be used for measuring intensely radio-active sources of gamma rays and beta particles. Scintillation counters also have been designed for detection of extremely low levels of alpha particles—of the order of one count every few minutes. Such counters are of particular value in environmental monitoring near plants processing uranium, plutonium, or other alpha-emitting materials. Scintillation counters are also being developed for neutron detection.

Colorimetric Detectors

When radiation reacts with a substance containing chlorine, carbon tetrachloride and water or chloroform

and water, for example, hydrochloric acid is formed. This in turn will cause a color change in certain dyes; and the amount of color change depends on the amount of radiation received. Such colorimetric detectors are largely in the experimental stage, but eventually the principle may be used to design a low-cost, simple dosimeter for personnel monitoring.

For Medical Use

A recent development in scintillation counting techniques at the Atomic Energy Project, University of California at Los Angeles, has provided a valuable tool for internal dosage measurements. One such instrument, *the tissue radiation fluorimeter*, uses a small internally light-reflecting "light pipe" inserted through a hypodermic needle. A small amount of fluorescent material is mounted in the tip. The scintillations or light flashes caused by alpha, beta, gamma, or X-rays are piped through the needle and counted in the usual way with a photomultiplier tube.

Radiation Exposures in AEC Plants

Compared to Natural and Diagnostic Exposures

From the Eighth Semi-annual Report of the Atomic Energy Commission.

NOTE: *r* signifies *roentgen*, a unit of measurement of the ionizing power of radiation, which is the factor that causes damage to living things.

Source of Radiation	*Amount of Radiation*
Cosmic rays, average	0.1 *r* a year
Cosmic rays, Denver, Colorado	0.5 *r* a year
Average annual exposure of *all* Hanford-Oak Ridge workers	0.2 *r* a year
Average 10 highest exposures of Oak Ridge workers	4.2 *r* a year
Routine chest X-ray*	0.5 to 5 *r* per exposure
Routine gastro-intestinal X-ray*	1.0 *r* per exposure
AEC permissible dose (for 20 years of exposure)	15 *r* a year at a rate of 0.3 *r* a week
Fluoroscopic examinations*	10 to 20 *r* a minute
Cinefluorography (X-ray movie)*	25 *r* per examination
Estimated lethal dose for 50 to 90 per cent of those exposed	400 to 600 *r*

* These exposures are to parts of the body. All others are whole-body exposures.

Elaborate Devices Guard Against "Run Away" Atomic Pile Danger

In Case of Disaster

From the Eighth Semi-annual Report of the Atomic Energy Commission

➤ IF FOR ANY reason the chain reaction in one of the Hanford piles were to "run away"—if the number of neutrons and of U-235 fissions were to multiply and remultiply out of the operators' control—the result would be disaster in the plant area. There could not be a nuclear explosion like that of a bomb, but the excessive energy and heat would probably breach the structure of the reactor, producing an airborne cloud of fission products and irradiated materials. This is one of the chief reasons why the plutonium plant was located in a 640-square-mile desert reservation. This is the reason, also why approximately 88,000 acres of the Wahluke slope, the region directly across the Columbia from the piles, must remain a part of the Government reservation. All points in this region are closer to the piles than the nearest inhabited area now existing.

The design of the piles makes a disaster virtually inconceivable except from such external causes as severe earthquake or successful enemy action. Besides the regular operating control rods, the pile is equipped with other quenching devices, each of which can stop the chain reaction. These devices do not depend upon human vigilance for their operation; any serious malfunctioning of equipment would set them in operation and automatically shut down the pile. The precautions against any such malfunctioning of equipment are similarly elaborate.

Unlikely as the event is, however, the operating and H.I. (Health Instrument) divisions at Hanford have carefully planned the moves that would be made if a pile "ran away." Emergency transport is continuously available, and periodic drills are held. The H. I. Divisions maintain a 24-hour service of radio-equipped cars. In the Hanford patrol headquarters in Richland, a control center has been set up. Information could be radioed to this center concerning the spread of radioactivity; the extent and movement of any discharge into the air could be charted; and evacuation of the plants could be directed by radio. A 12-man emergency monitoring team has been established, equipped with kits of survey and protective equipment and trained in surveying, posting, and mapping the radioactive contamination that might exist in some critical area.

Atomic Weight Difference Solved Puzzle of Elements

Naming the Isotopes

A Classic of Chemistry

THE INTERPRETATION OF RADIUM *and the Structure of the Atom, by Frederick Soddy, 4th ed. G. P. Putnam's Sons, New York, 1920.*

➤ IN 1911 the writer pointed out that the products of *a*-ray changes have a certain definite relationship in chemical character to their parents. The chemical properties of an *a*-ray product correspond with those of an element in the periodic table with group number two *less* than that of the parent. Thus, radium in Group II expels an *a*-particle and changes into the emanation in Group O, ionium in Group IV changes by expulsion of an *a*-particle into radium in Group II, and so on. It was also noticed that the passage through the periodic table of the element undergoing change was frequently alternating, the products frequently reverting in chemical nature to that of an earlier parent. So radiothorium resembles thorium, thorium X, mesothorium I, and so on.

This curious atavism has now been very simply and fully explained, largely owing to the chemical investigations of Alexander Fleck in the writer's laboratory at Glasgow, who spent three years in the exhaustive study of the chemical nature of all the radioactive elements, which survive for a long enough period for their chemical nature to be determined, and many of which had previously been very imperfectly investigated from this standpoint.

In consequence, the generalization already alluded to has come to light. It was seen that the expulsion of a β-particle was entirely analogous to that of the expulsion of the *a*-particle, but that, instead of the product possessing a chemical nature corresponding with an element in the periodic table with group number two less than the parent, it corresponded with an element of group number one greater. Hence if, in any order, one *a*- and two β-rays are expelled, the product is chemically of the same nature as its parent, and the curious atavism referred to above is explained.

Radioactive children frequently resemble their great-grandparents with such complete fidelity that no known means of separating them by chemical anaylsis exists. But, of course, the two intermediate parents are readily separated. By this means all the members of the family may be recognized severally, although, but for this means, that would be still impossible.

The complete generalization, which was put forward in 1913 independently during the same month by A. S. Russell, K. Fajans, and the writer, is as follows. The last twelve places of the periodic table, from uranium to thallium, are placed consecutively side by side, and the passage of the elements, in the uranium, thorium, and

actinium series, from place to place, as the *a*- and β-ray changes succeed one another, is indicated by arrows. The figure is to be read at 45°, so that the lines showing the atomic weights are horizontal.

Every detail of the chemical nature of the members of the known sequences in the uranium, thorium, and actinium series, including the complicated branchings which occur toward the ends, bears out implicitly these two simple rules. Independently of their origin, atomic weights, and radioactive character — that is, of the kinds of change they are about to undergo — all the members of the three disintegration series, which, by the consistent application of these rules fall into *the same place* in the periodic table, are chemically completely identical and non-separable from one another. Hence I have termed them *isotopes or isotopic elements*. . . .

The existence of such isotopic elements would not have been suspected except for radioactive changes. What fixes the chemical and general material character of an element is a particular numerical charge, and this charge is not the total charge of the atom, but is the net charge of the nucleus or the difference between the numbers of positive and negative charges which it contains. The same net charge may be, and, in the case of isotopes, is made up of different absolute numbers of positive and negative charges differing by the same amount. When an *a*- and two *β*- particles are successively expelled the net charge becomes again what it first was, and the position in the periodic table and whole chemical character also reverts to the initial state. But the atomic mass is different by four units, the mass of the *a*-particle expelled.

Electron Spin

➤ UNDER THE COMPULSION of experiment, Uhlenbeck and Goudsmit (1925) put forward the following bold hypothesis. Previously the electron was regarded as an unextended structure, possessing only three degrees of freedom and, moreover, determined by two constants, *viz.* its charge *e* and its mass *m*. If, however, the electron is regarded as a structure with finite extension, then, like every extended system, it possesses three rotational degrees of freedom besides its three translational freedoms. It is therefore an obvious suggestion to ascribe to the electron angular momentum about an arbitrary axis (also frequently called "mechanical moment"). Developing the idea further, we must assume that the electron also possesses magnetic moment; for the electron carries an electric charge *e*, which rotates convectively, about the axis mentioned, along with the electron; so that the rotation electron is equivalent magnetically to a system of circular currents round the axis of rotation, and these, as we know, give rise to a magnetic moment. With regard to the magnitude of the magnetic and the mechanical moments, experiment must of course decide in the first instance; afterwards, we can try to deduce these magnitudes theoretically. This property of the electron, in virtue of which it has a mechanical and a magnetic moment, is called its *spin*.

—*Born: Atomic Physics*

Radioactive Tracers Measure Minute Quantities of Matter

First Tracer Chemistry

A Classic of Chemistry

A new technique was pioneered in this paper by the Danish chemist who, less than ten years later, was one of the discoverers of the element Hafnium. Tracer methods become more important year by year.

RADIO-ELEMENTS AS INDICATORS IN CHEMISTRY AND PHYSICS. *By G. Hevesy, Ph.D. In Chemical News, London, Vol. 108, Oct. 3, 1913.*

➤ BY MEANS of an *a*-ray electroscope of ordinary sensitiveness it is possible to measure accurately as small a quantity as 10^{-17} grms. of a radio-active substance having a half-value period of one hour. The extraordinary simplicity and at the same time sensitiveness with which it is possible to measure these extremely small quantities of radio-active bodies makes them of the greatest use not only in studying substances in great dilution but also as indicators of physical and chemical processes.

Radio-active indicators may be conveniently divided into two principal groups. To the first group belong those whose use as indicators depends only on their physical properties and not on their chemical properties. Some examples of the use of radio-active indicators of this kind are the following:—

It is only necessary to know that the radio-elements composing the active deposits are metals in order to test the formula of Arrhenius connecting the variation of velocity of solution of metals in acids with the temperature. This has been lately carried out by Miss Ramstedt.

It is known from the kinetic theory that the concentration of a solution varies with time, and this problem, which could not be attacked by ordinary methods, has been made experimentally feasible by the use of radio-active bodies as indicators. (Svedberg, Smoluchowski).

The existence of colloidal solutions of radio-elements has been lately established by Paneth and Godlewski, and experiments have been undertaken on the formation and precipitation of these colloids using radio-active indicators.

The emanations, the only gaseous radio-elements, have been employed to establish the validity of the gas laws, especially that of Henry's law for extremely small partial pressures. (Bruhat, Boyle).

Fick's Diffusion Law has also been shown to hold accurately for bodies in infinitely small concentration by making use of radio-active substances.

It is often a question of practical interest to the chemist to know how often it is necessary to wash out a pipette or a beaker in order to remove the last trace of the solution it had contained. This problem can be

investigated with extreme ease when radio-active indicators are used.

The fact, however, that most radio-elements are throughout in all chemical properties exactly similar to some of the common elements (for instance, radium D and thorium B are non-separable from lead, thorium C and radium E from bismuth, etc.) allows these bodies to be used chemically as indicators of the bodies from which they are known to be non-separable. Radium E can be used as an indicator for bismuth, radium D for lead, etc.

If 1 mgrm. of lead is mixed with a quantity of radium D which gives 10,000 units of activity in an electroscope, one-millionth part of this mixture is easily detectable by the radio-activity of radium D. In this way 10^{-6} mgrms. lead is quantitatively determinable.

By this method also the solubility of the difficultly soluble salts of lead, such as the chromate and the sulphide, has been determined. Further, the amount of lead chloride entrained by a precipitate of silver chloride after washing the latter thoroughly with water is measurable.

Experiments on the electrochemical behavior of small quantities of lead and bismuth have been begun. By means of these indicators a study may be made of the electrochemical behavior of these metals for electrode potentials lying below the decomposition voltage, a problem which could not be investigated by any other means.

Of especial use are the indicators for investigating the diffusion and mobility of ions in extremely small concentration. Data are already available on the diffusion rate of lead salts down to a normality of 10^{-14}.

Neutrons Locate Hydrogen in Crystals

➤ NEUTRONS, which stream from the chain reactor gave Drs. C. G. Shull and E. O. Wollan of the Oak Ridge National Laboratory the opportunity to use this stream of vibrating neutral particles as though it were a beam of light. The scientists in 1948 found that they could pass a neutron beam through a crystal, and make it reveal the crystal's atomic structure by knocking electrons out of induim foil placed over photographic film.

With the older techniques it was impossible to locate hydrogen atoms. Neutrons show up hydrogen along with all the other elements. Thus at once there is opened a new field of investigation into the structure of myriads of organic chemicals.

The neutron beam adds to X-rays and electrons a third kind of probe into the structure of crystals. Each probe gives a different sort of information. But with the neutron beam several new problems present themselves. Neutrons are not energy units, they are matter. They are some 1800 times as heavy as electrons. They act like a gas. Nevertheless, because their ultimate particles are still very small, they also behave like waves.

Lightweight Particles Required By Rutherford's Atom Theory

Prediction of the Neutron

A Classic of Chemistry

From Aston's discoveries with a primitive form of the mass spectrograph, Rutherford postulated the structure of the atomic nucleus as a close combination of electrons with hydrogen nuclei. He predicted the discovery of the neutron, of deuterium and of the two particles of mass 3; tritium, an isotope of hydrogen, and He^3, whose production in quantity in the atomic pile has just been announced. To put Rutherford's descriptions into modern phraseology, read "neutron" for each pair consisting of hydrogen nucleus and tightly bound electron, and "proton" for each hydrogen nucleus without the electron. The quotation below is but a part of the lecture.

NUCLEAR CONSTITUTION OF ATOMS, *Bakerian Lecture by Sir E. Rutherford. Proc. Roy. Soc. A97 (1920).*

➤IN CONSIDERING the possible constitution of the elements, it is natural to suppose that they are built up ultimately of hydrogen nuclei and electrons. On this view the helium nucleus is composed of four hydrogen nuclei and two negative electrons with a resultant charge of two. The fact that the mass of the helium atom 3.997 in terms of oxygen 16 is less than the mass of four hydrogen atoms, viz., 4.032, has been generally supposed to be due to the close interaction of the fields in the nucleus resulting in a smaller electromagnetic mass than the sum of the masses of the individual components.

Sommerfeld has concluded from this fact that the helium nucleus must be a very stable structure which would require intense forces to disrupt it. Such a conclusion is in agreement with experiment, for no evidence has been obtained to show that helium can be disintegrated by the swift α particles which are able to disrupt the nuclei of nitrogen and oxygen.

In his recent experiments on the isotopes of ordinary elements, Aston* has shown that within the limit of experimental accuracy the masses of all the isotopes examined are given by whole numbers when oxygen is taken as 16. The only exception is hydrogen, which has a mass 1.008 in agreement with chemical observations. This does not exclude the probability that hydrogen is the ultimate constituent of which nuclei are composed, but indicates that either the grouping of the hydrogen nuclei and electrons is such that the average electromagnetic mass is nearly 1, or, what is more probable, that the secondary units, of which the atom is mainly built up, *e.g.*, helium or its isotope, have a mass given nearly by a whole number when oxygen is 16.

The experimental observations made so far are unable to settle whether the new atom has a mass exactly 3, but from analogy with helium we may expect the nucleus of the new atom to consist of three H nuclei and one elec-

* Phil. Mag. Dec. 1919; April and May 19

tron, and to have a mass more nearly 3 than the sum of the individual masses in the free state.

If we are correct in this assumption it seems very likely that one electron can also bind two H nuclei and possibly also one H nucleus. In the one case, this entails the possible existence of an atom nearly 2 carrying one charge, which is to be regarded as an isotope of hydrogen. In the other case, it involves the idea of the possible existence of an atom of mass 1 which has zero nucleus charge.

Such an atomic structure seems by no means impossible. On present views, the neutral hydrogen atom is regarded as a nucleus of unit charge with an electron attached at a distance, and the spectrum of hydrogen is ascribed to the movements of this distant electron. Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet.

Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope, and it may be impossible to contain it in a sealed vessel. On the other hand, it should enter readily the structure of atoms, and may either unite with the nucleus or be disintegrated by its intense field, resulting possibly in the escape of a charged H atom or an electron or both.

If the existence of such atoms be possible, it is to be expected that they may be produced, but probably only in very small numbers, in the electric discharge through hydrogen, where both electrons and H nuclei are present in considerable numbers. It is the intention of the writer to make experiments to test whether any indication of the production of such atoms can be obtained under these conditions.

The existence of such nuclei may not be confined to mass 1 but may be possible for masses 2, 3, or 4, or more, depending on the possibility of combination between the doublets. The existence of such atoms seems almost necessary to explain the building up of the nuclei of heavy elements; for unless we suppose the production of charged particles of very high velocities it is difficult to see how any positively charged particle can reach the nucleus of a heavy atom against its intense repulsive field.

We have seen that so far the nuclei of three light atoms have been recognized experimentally as probable units of atomic structure, viz.,

H_1^+ X_3^{++} He_4^{++}

where the subscript represents the mass of the element.

Heisenberg's Uncertainty Principle

➤ THE RANGE of uncertainty of the position of a particle, multiplied by the range of uncertainty of its momentum, will always be of the order of magnitude of the constant: $h/2\pi$. Such uncertainties can never be detected experimentally, since the act of making the observation would disturb the position or the momentum of the particle by amounts as great as those given by this principle.

—*Brown*: *Fundamentals of Modern Physics.*

Triple Weight Hydrogen Discovered by Rutherford

The First Tritium

A Classic of Chemistry

TRANSMUTATION EFFECTS OBSERVED WITH HEAVY HYDROGEN, *by M. L. E. Oliphant, P. Harteck and Lord Rutherford, in Philosophical Transactions of the Royal Society, London, Vol. A 144, pp. 692-703, May 1934. (Excerpted).*

➤ THE MOST interesting and important reaction which we have observed is that of heavy hydrogen on heavy hydrogen itself. Experiment has shown that diplogen* is not appreciably affected by bombardment with X-particles from polonium, and we have been unable to detect any specific action of protons on diplogen for energies up to 300,000 e-volts. We were therefore surprised to find that on bombarding heavy hydrogen with diplons* an enormous effect was produced. We assumed at first that this was an effect due to radiation passing through the counting chamber as previous experiments had shown that X-rays could produce just the results observed, but subsequent observation at much lower bombarding potentials showed that we were dealing in reality with a very large emission of protons. The original observations were made on ND_4Cl, but in order to establish that the effects observed came from the action of D on D and not from the nitrogen or chlorine, we bombarded targets of $(ND_4)_2SO_4$ and of D_3PO_4.

It is evident that there are present in each case two very prominent groups of particles of ranges 14.3 and 1.6 cm. respectively. Careful counting of the records established that the numbers of these particles were identical within the errors of measurement. The maximum size of the deflection produced on the oscillograph record by the particles in each group indicated that they both consisted of singly charged particles. On these data it is natural to assume that the particles are emitted in pairs opposite one another, and that the difference in range arises from a difference in mass, and hence of the velocity and energy. The simplest reaction which we can assume is

$$ {}_1D^2 + {}_1D^2 \rightarrow {}_2He^4 \rightarrow {}_1H^1 + {}_1H^3 \qquad (1) $$

While from the point of view of both experiment and theory, we have no information of the details of the nuclear changes involved and can only study the final result, yet it is often useful and may even be more correct to assume that the first step in the process is the capture of the bombarding particle to form a new and heavier nucleus. If this proves unstable, it then breaks up, possibly in a variety of ways. The recent discovery by M.

* *Diplogen* is now called deuterium, and the *diplon* is the deuteron.—Ed.

and Mme. Curie-Joliot, and by Cockcroft and Walton, that a type of radioactive nucleus is formed by the capture of an X-particle, diplon or proton lends support to this point of view. The time of transformation may vary over very wide limits and may sometimes be so short that the process cannot be experimentally followed. In the case which we are considering we are inclined to interpret the observations in the following way. The initial process is the union of two diplons to form a new nucleus of charge 2 and mass 4, *i.e.*, a helium nucleus. If we neglect the energy of the bombarding particle and assume the mass of D to be that given by Bainbridge, the mass of this helium atom must be 4.0272, and it therefore possesses an execess energy over the normal helium atom, of mass 4.0022, of about 23 million volts. This atom is unstable and may lose its energy in a variety of ways, some of which are considered later. We are considering here the breaking up of the helium nucleus into a proton and a hydrogen isotope of mass 3. The transformation follows so rapidly after the capture that no evidence of the existence of the excited helium nucleus has so far been obtained.

The mass and energy relations on the right-hand side of equation (1) can be obtained in the following way. The $_1H^1$ particle possesses an energy of 3.0×10^6 e-volts, corresponding to protons of the observed range of 14.3 cm. Then, from momentum considerations, the energy of the $_1H^3$ particle which is emitted in the opposite direction will be $1.0 \times 10_6$ e-volts, *i.e.*, the total energy of the two particles will be 4.0×10^6 e-volts, corresponding to a mass-change of 0.0043 units. Hence the mass of the $_1H^3$ atom will be

$$4.0272 - (1.0078 + 0.0043),$$

i.e., 3.0151. The ionization produced by the $_1H^3$ particle will be at every point of its path identical with that produced by a proton possessing the same velocity. However, owing to its greater momentum the $_1H^3$ particle will travel three times as far as the proton for a given reduction of velocity. Consequently it will have three times the range of a proton of the same initial speed. The initial velocity of the $_1H^3$, corresponding to an energy of 10^6 e-volts, is 8×10^8 cm/sec. The range of a proton with this velocity is 5.8 mm. according to data given to us by Feather. Hence the range of the $_1H^3$ particle should be $3 \times 5.8 = 1.74$ cm. Considering the nature of the data available and the difficulties of determining the range of the short 1.6 cm. group accurately, we feel that this agreement is very satisfactory.

Additional evidence of the truth of our assumption is afforded by observation of the way in which the ionization, as measured from the magnitude of the oscillograph deflections, varies near the end of the range of the particles. We have plotted the number of deflections above a given size against the absorption in the path of the particles, using a chamber 3 mm deep. It is seen that the 14 cm group shows a very sharp peak which occurs about 2 cm short of the end of the range. The 1.6 cm group, on the other hand, rises rapidly to what appears to be a much broader maximum. This is just what would be expected.

Important Patent Issued to Fermi Before Atomic Energy Blackout

Slow Neutron Bombardment

A Classic of Chemistry

Long before nuclear fission was recognized, this prototype of the atomic energy pile was envisioned by a group of physicists in Italy. Among them will be recognized key developers of the atomic bomb in America.

UNITED STATES PATENT OFFICE — 2,206,634 (Patented July 2, 1940)—PROCESS FOR THE PRODUCTION OF RADIOACTIVE SUBSTANCES. Enrico Fermi, Edoardo Amaldi, Bruno Pontecorvo, Franco Rasetti, and Emilio Segre, Rome, Italy, assignors to G. M. Giannini & Co., Inc., New York, N.Y., a corporation of New York. Application October 3, 1935, Serial No. 43,462. In Italy October 26, 1934.

➤ THIS INVENTION relates to the production of isotopes of elements from other isotopes of the same or different elements by reactions with neutrons, and especially to the production of artificial radio-activity by formation of unstable isotopes.

It has been known for many years that, although each chemical element has always the same atomic number or charge, it may exist in different forms having different atomic weights. These forms of the elements are referred to as isotopes.

It has also been known that the radio-active elements, by disintegration or break down occurring in their nuclei are spontaneously converted into various isotopes of other elements. Thus, for example, the radio-active element uranium may be converted into lead of atomic weight 206, while the element thorium may be converted into a different isotope of atomic weight 208.

It has long been known that such spontaneous disintegration of radio-active elements is accompanied by emission of alpha, beta, and gamma rays, that is to say, of the helium nucleus, electrons, and electromagnetic radiation of extremely short wave length.

In more recent years it has been demonstrated that isotopes of various elements could be converted into other isotopes of the same or different elements by bombardment with alpha particles, diplons, protons or gamma rays of very high energy, and that the isotopes thus produced may be unstable so as to decompose with features similar to those of the naturally radio-active bodies. That is to say, radio-active isotopes may, in this way, be artificially produced.

Accordingly, it is an object of the present invention to provide a method and apparatus by which nuclear reactions can be carried on with high efficiency and with the heavier as well as with the lighter elements. A more specific object of the invention is to provide a method and apparatus for artificially producing radio-active substances with efficiency such that their cost may be brought below that of natural radio-active materials.

Our invention is based upon the use of neutrons instead of charged particles for the bombardment and transformation of the isotopes.

All of the prior work on nuclear reactions has been done with high energy particles and every effort has been bent toward increasing the energy of the particles as the means of extending and making more efficient the nuclear reactions. We have now discovered that effort in this direction is sound only when charged particles are used which require tremendous energy to break through the potential barrier surrounding the nucleus; and that if, instead of charged particles, neutrons are used for the nuclear reactions, the greatest efficiencies are in some cases attained with low energy or "slow" neutrons, e.g., of the order of a few hundred electron volts, or even much less down to a small fraction of an electron volt.

Neutrons when produced in any ordinary manner, e.g., by the action of radon on beryllium or of polonium on beryllium or by bombardment of atomic nuclei with artificially accelerated particles, might have a very wide range of energies but high average energy. These energies range up to several million volts. It is necessary, therefore, if the greatest efficiency of reaction is to be attained, to reduce by artificial means the energy of these neutrons. We describe below a method for slowing down fast neutrons.

We have demonstrated that the absorption of slow neutrons is anomalously large as compared with that of the faster or higher energy neutrons. The simplest explanation for most cases is to admit that the neutron is captured by the nucleus with formation of an isotope heavier by one mass unit. If this heavier isotope is unstable a strong induced radio-activity may be expected. This occurs, for example, with silver and iridium which go over into radio-active isotopes. In other cases it is found that no activation, or at least no strong activation, follows an anomalously large absorption. This is the case with many elements, e.g., yttrium and cadmium. In these cases the formation of a stable nucleus upon the capture of the neutrons is to be expected.

In some cases the absorption of the slow neutrons results in the emission of a relatively strong gamma-radiation with energy corresponding to the binding energy of the neutron. This gives a reliable source of very hard gamma rays, even harder than the naturally produced gamma rays, e.g., from radium.

In view of these considerations it is obviously desirable to convert as many as possible of the available neutrons into the slow or low energy condition in which they may be readily captured by the nuclei of the substance being reacted. We have found that it is possible to achieve the desired results by passing the neutron radiation against or through a screen of a suitable material.

The materials which have been found best suited to this purpose are those containing hydrogen (including all its isotopes, but the light isotope which predominates in natural occurrence being most efficient) and especially water and the hydrocarbons, such as paraffin for example. Other materials, as for example beryllium, carbon, silicon, lead, show this effect to a lesser

degree. Other materials, of which iron is an example, do not produce a similar effect to any practical extent, probably because of a relatively large absorption of the neutrons when their energy is reduced.

The increase in activity of the neutrons by such substances is apparently due to two effects both resulting from collisions of the neutrons. In the first place it is readily shown that an impact of a neutron against a proton reduces, on the average, the neutron energy by a factor $1/e$. From this it follows that ten impacts reduce the energy to about 1/20,000 of its original value. Assuming the initial energy to be $4 \cdot 10^6$ electron volts, the energy after ten impacts would be about 200 electron volts and 20 impacts would reduce the energy of the neutron down to a value corresponding to thermal agitation. Thus the first important effect is probably the reduction of the energy of the faster neutrons by impact and the efficiency of hydrogen for this purpose is probably due to the low mass of the hydrogen nucleus. Although we refer to the nucleus, because almost the entire mass is represented by the nucleus, it will be understood that the impact for slowing down may be, and for reasons of economy, ordinarily will be, with atoms, i.e., combined nuclei.

The second probable effect is the scattering and reflection of the neutrons.

Hydrogen is so much more effective than any of the other elements for reducing the energy of neutrons that it will ordinarily be used. It must not be overlooked, however, that the elements having a lesser effect offer possibilities for control of the neutron energy. Where neutrons of initially lower energy are used or where their use requires a higher energy than in the reactions with which we are here especially concerned, the less effective elements may be used singly or combined with elements of different energy reducing power.

The density of the energy reducing or scattering substance has also been found to be an important factor. This follows, likewise, from the theoretical explanation given above. If the energy reduction and scattering of the neutrons is due to impact with atomic nuclei, the probable frequency of such impacts will be directly dependent upon the number of atoms in a given space. For this reason such substances ordinarily should be used in liquid or solid (i.e., non-gaseous) form and, so far as is practicable, substances will be chosen having as high as possible a proportion of hydrogen in the molecule. Here again, the gaseous state under various pressures, and substances having less hydrogen offer the possibility for accurate control if less than the maximum slowing of neutrons is desirable.

It will be readily understood from what has been said above that the greatest effect is attained if the source of neutrons and the substance being irradiated are both surrounded by the energy reducing and scattering material. This could easily be accomplished in many cases by immersing the neutron source in a solution or emulsion of the substance being bombarded. We have illustrated diagrammatically in Figures 1 and 2 arrangements by which this may be accomplished.

In Figure 1 a cylindrical paraffin block 10 is provided with a hole 11 in-

to which is inserted a source of neutrons, e.g., a tube containing radon and beryllium. The material being irradiated is placed above the source on the paraffin block as shown at 12 and is covered by a second paraffin block 13 having a central opening 14 to accommodate the material being irradiated. For the treatment of small amounts of materials the block 10 may be, for example, about 24 centimeters in diameter and about 14 centimeters in height with the neutron source about 2 centimeters under the upper surface. It will be observed that these dimensions give radial thickness of the material surrounding the neutron source approximately equal to the mean free path in the substance of the high energy neutrons.

Where the substances to be irradiated are soluble in or can be suspended in water or a hydro-carbon or other energy reducing or dispersing substance, etc., may be formed and the substances irradiated therein by immersing the neutron source directly into the solution, etc. (See Figure 2.)

The hydrogen which serves to reduce the energy of the neutrons may also be in chemical combination with the substance being irradiated.

Figure 2 is a diagrammatic illustration of a neutron irradiating device in which the substance being irradiated is dissolved or dispersed in the energy reducing or dispersing material. A suitable vessel 20 is provided for holding the solution or dispersion 21 and into this is immersed the neutron source 22.

Instead of the radon beryllium source, any other source of neutrons may be used, as for example neutron tubes as developed by Oliphant and

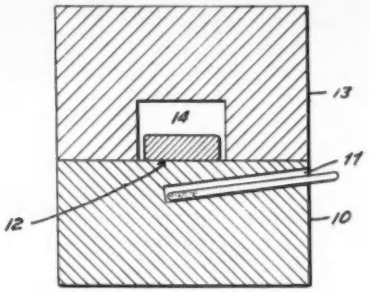


Fig. 1

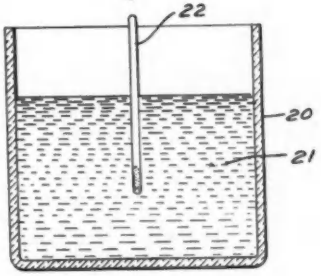


Fig. 2

as more recently developed by laboratories of the General Electric Company and the Westinghouse Electric and Manufacturing Company or cyclotrons as developed by Lawrence. In such tubes deuteron oxide (heavy water), which may be separated by known methods from naturally occuring water, is bombarded with deuterons accelerated in an electric field produced by a grid tube. The deuteron nucleus is disintegrated with the emission of neutrons.

Obviously the apparatus can be endlessly modified, the essential being the combination of the energy reducing substance near the substance being irradiated, and a suitable source of neutron radiation.

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